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OF CIVIL ENGINEERS

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Journal of the
SANITARY ENGINEERING DIVISION
Proceedings of the American Society of Civil Engineers

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CONTENTS

October, 1957

Papers

	Number
Nuclear Long-Range Fallout in Surface Waters by Carlos G. Bell, Jr.	1400
Sanitary Engineering and Reactor Waste Disposal by J. G. Terrill, Jr., and M. D. Hollis	1407
Dispersal of Pollution by Tidal Movements by Thomas M. Niles	1408
Anaerobic Reduction of Manganese in Reservoirs by John H. Weideman and Robert H. Fetner	1409
Niagara River Pollution by Raymond W. Hess	1410
Liquid Content of Garbage and Refuse by John S. Wiley	1411
Discussion	1422
Settling Behavior of Waste Suspensions by Vaughn C. Behn	1423

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Paper 1400 October, 1957 SA 5

Journal of the
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NUCLEAR LONG-RANGE FALLOUT IN SURFACE WATERS[a]

Carlos G. Bell,[1] Jr., A.M. ASCE
(Proc. Paper 1400)

SYNOPSIS

Emphasis is placed on measurements for and calculation of runoff coefficients of gross long-range fallout beta radioactivity for several streams in eastern Massachusetts and the Genessee River in New York. Measurements and analyses are presented that strongly indicate a selective uptake of certain radioactive nuclides in recently deposited fallout, although no individual species was identified. Solubility of long-range fallout, its sedimentation, and its rate of dissipation after deposition is discussed.

This paper summarizes a portion of the work done at Harvard University between April, 1952, and December, 1954,(3,4,5) on this problem from the point of view of the sanitary engineer. No attempt will be made here to answer questions of genetic effects. However, it is hoped that the measurements presented will help serve as a basis for calculation by geneticists. Incidentally, those arguing on long-range fallout hazard are putting more and more emphasis on genetic effects at the expense of radiation sickness and internal radiation. This heads the argument away from the questions involving water supply. There has been some discussion of genetic effect on the somatic cells(13) and on the reproduction cells by internal emitters.(14) However, somatic cell genetics is just beginning to be studied(13) and it seems quite unlikely that the internal irradiation of reproductive cells is of primary importance. If the long-range fallout hazard argument is based on genetic effects, it is very unlikely that any unanimous expert opinion will soon appear.(1,2) Of course the problem extends beyond that of fallout to the entire field of the use of radioactive materials.

Note: Discussion open until March 1, 1958. Paper 1400 is part of the copyrighted Journal of the Sanitary Engineering Division of the American Society of Civil Engineers, Vol. 83, No. SA 5, October, 1957.

a. Presented at a meeting of the American Society of Civil Engineers in Knoxville, Tenn., June 1956.

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Most of the conclusions presented here are based on measurements made on surface waters collected routinely from approximately fifteen eastern Massachusetts streams and reservoirs between March, 1952, and July, 1953. In addition the author was given measurements made by the Massachusetts Department of Public Health and other measurements made in the vicinity of Rochester, New York. Altogether about 80,000 measurements were taken on some 10,000 samples.

Nature of Fallout Particles

Careful measurements[6] of the short range (70 miles) fallout on the fishing ship Fukuryu Maru on March 1, 1954, during the Pacific "Castle" test series indicate particles in a size distribution that is arithmetically normal about a mean of 278 μ with a standard deviation of 78 μ. Size separation may have taken place between the fallout and its collection. On the other hand, long range fallout particles are generally much smaller, usually being less than a few microns in diameter, although a 22 μ particle from the Nevada detonation of March 18, 1952, was reported found on a Mr. Bradshaw's shirt button at Oak Ridge, Tennessee, on the following day.[7]

A knowledge of the particles' size distributions, shapes, densities, surface characteristics, solubitities, porosities, and resistances (to weathering, crushing, and erosion) is necessary for a complete study of long-range fallout by sanitary engineers for their understanding of retention and runoff of fallout radioactivity from water sheds, uptake by algae and suspended solids in water, deposition on the bottoms of streams and reservoirs, and passage through the various stages of water treatment plants. The sanitary engineer is not justified in assuming that all measurements of the type that he needs have already been made. However, an appreciable amount of information can be fitted together to give a first picture of the situation.

A listing has been made,[8] based on thermodynamic considerations, of the chemical compounds most likely formed as the material in a nuclear fission detonation fireball cools. It has been concluded that little separation takes place between the points of complete condensation and deposition,[9] but separation does occur in the condensation of fireball gas that goes to the solid phase. In the cases of strontium (Sr^{90}) there is a depletion of the species in the near-detonation fallout at the expense of about a three-fold enrichment in the long-range fallout.[10] This mechanism consists of precursors decaying soon after fission through a short-lived Krypton gas phase to radiostrontium species and finally to their daughters, which would tend to place the strontium near the particle surface. This tendency would reduce the chances that large portions of the radiostrontium's passing into and through water treatment plants and also through the human gastro-intentinal tract encapsulated in relatively insoluble particles. It appears quite possible that even if radioactive fallout material is relatively insoluble while in surface waters or during the water treatment process, it will go into solution in the stomach (where the pH is 2.3) and be in part retained in the body.

Rain Conducted Fallout Dialysis, Filtration and Sedimentation

Previously unreported dialysis measurements made near Rochester, New York on Nevada-created fallout prior to any announced fusion detonations indicated that the portion of rain-precipitated long-range fallout that passed a paper filter was in solution. Thirty-eight liters of rain collected on June 3-4,

1951, was left stagnant for eight days; the supernatant was evaporated to 730 ml. in a glass container, then filtered through a Whatman No. 40 paper; the filtrate was placed in a cellophane bag suspended in a cylinder containing 500 milliliters of distilled water so that the heights of water inside and outside the bag were equal. This was allowed to stand for five days with occasional stirring and the solutions inside and outside the bag were evaporated and counted on June 18, 1951 with a Geiger-Müller tube having an end window of 2.3 milligrams per square centimeter. The net count rates were 283±5.4 cpm for the evaporated solution that was inside the bag and 279±5.4 cpm for that outside. Therefore it was indicated that the material was in solution. The bag was tested for leaks by filling with distilled water and placing as before but with the addition of a few drops of India ink to the water inside the bag. No migration occurred. A repeat run was then made using potassium iodide in solution in distilled water. Equal concentrations inside and outside the bag were reached in three days. On June 4, the day of collection, four liters of the same rain were filtered through a Whatman No. 40 paper. The evaporated filtrate registered a net count rate of 49 counts per minute per liter.

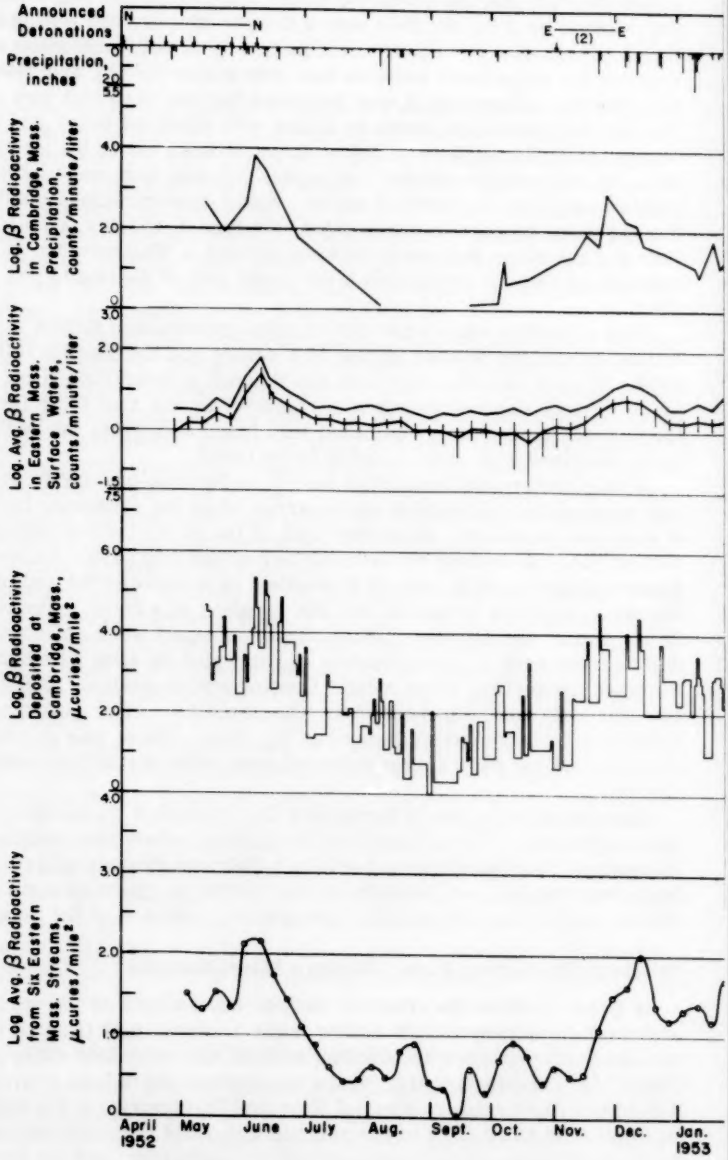
Five filtration tests were run on rain-precipitated fallout in Massachusetts following both the Nevada spring test series and the Pacific fall test series of 1952. In each case the rain was run through a membrane filter. Twice as much Nevada-created debris was removed as was that from the Pacific. The former was presumably combined with fused soil while the latter must have been combined with more soluble fused coral.

A preliminary sedimentation test[3] on Nevada-created fallout indicated that appreciable sedimentation occurred when the rainwater that accompanied it was held quiescent. More than half of the gross beta-emitting material settled near the bottom of the container within two days. Following the Eniwetok test in 1952, rain of November 22 was collected and placed in eight 500 ml. graduated cylinders and left standing in a room maintained at 20°C. At the end of one day, five 100 milliliter samples were collected at various depths from each of two cylinders of rainwater by slow withdrawal of the water at the surface using a light floating siphon device. At the end of three, five and eight days this procedure was repeated. After collection, the fifty samples were counted on December 27, 1952. There was no evidence of sedimentation of the radioactive material even when statistical methods were employed.

Samples of the rains of November 22, December 5, and December 14, 1952 were collected in crocks and held for approximately two months. One-liter volumes of rainwater were carefully withdrawn through polyethylene tubes from near the tops and bottoms of the crocks, evaporated and counted. No sedimentation was indicated by a statistical analysis of the count rates.

Radioactivity Survey Plots: Eastern Massachusetts

In order to show the effect of nuclear detonations on the surface waters of eastern Massachusetts, the author made a survey plot (Figure 1) that relates the dates of announced detonations with (a) the estimated daily precipitation at Cambridge, Massachusetts; (b) the concentrations of beta radioactivity that fell on the Cambridge campus of Harvard University; (c) the average concentrations of radioactivity in the surface waters of the collection area; (d) the daily areal deposition of radioactivity in Cambridge; and (e) the areal "runoff" of radioactivity from watersheds in the collection area.


Announced Detonations
N
N
E
(2)
E
Precipitation, inches
0
2.0
5.5
Log. β Radioactivity in Cambridge, Mass. Precipitation, counts/minute/liter
4.0
2.0
0
Log. Avg. β Radioactivity in Eastern Mass. Surface Waters, counts/minute/liter
3.0
2.0
0
-1.5
7.5
Log. β Radioactivity Deposited at Cambridge, Mass., μcuries/mile²
6.0
4.0
2.0
0
Log Avg. β Radioactivity from Six Eastern Mass. Streams, μcuries/mile²
4.0
3.0
2.0
1.0
0
April 1952
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1953

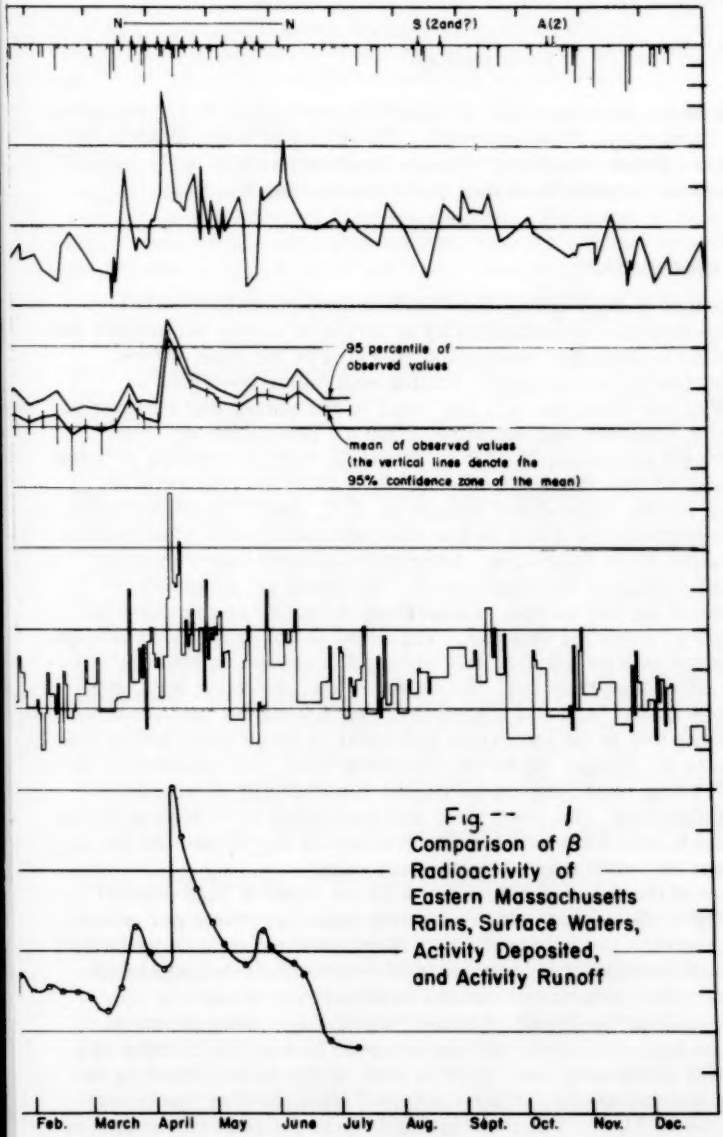


Fig. -- 1
Comparison of β Radioactivity of Eastern Massachusetts Rains, Surface Waters, Activity Deposited, and Activity Runoff

At the top of Figure 1 are noted the dates of announced detonations from April, 1952 to the end of 1953. "N" stands for detonations in Nevada, "E" for Eniwetok, "S" for Siberia, and "A" for Australia. It is probably incomplete, for the United States Atomic Energy Commission discontinued, at least temporarily, the publication of the detection of foreign tests after announcing the first two detonations of the 1953 series of the Soviet Union.

Precipitation

Just below the bomb detonation plot is shown the estimated daily precipitation in inches at Cambridge, Massachusetts. These values were obtained by averaging the United States Weather Bureau's measurements of daily rainfall at Logan International Airport, Blue Hill Observatory, and Waltham, Massachusetts.

Radioactivity of Precipitation

The plot below that of the rainfall shows a line connecting the plotted values of the concentrations of radioactivity in terms of counts per minute per liter of precipitation in samples collected at Harvard at the time of first counting as registered by the automatic scaling equipment described in Reference (5). With the exception of a few rains in the spring and summer of 1952, samples were collected and measured from all precipitations from May 12, 1952, through December 31, 1953. The time of first counting of these samples was almost always from one to three days after the precipitation, which is sufficient for the short-lived radium A, B, C, and C' (Po^{218}, Pb^{214}, Bi^{214}, Po^{214}, respectively) to decay to low concentrations, as well as thoron (Em^{220}) and its short-lived daughters. Although repeated measurements were made on each sample of precipitation (as on almost all samples collected), no correction for the sample radioactivity decay between collection and first counting was made for this plot. The mass of the evaporated precipitation sample residue was so low that self-absorption caused an average decrease in count rate of less than 10%. No rinses of the collecting apparatus for dry fallout were made. At least a portion of the dry fallout that occurred must have been deposited in the collection apparatus (a large sheet metal funnel) and washed into the sample jug by the following rain. The experience of the author indicates that most long-range fallout radioactivity is brought to the ground by precipitation. However, good measurements have been made at Rochester, New York, that show areal concentrations of dry fallout almost as large as the largest recorded there accompaning rain.

In a comparison of the dates of detonation with the dates of high concentration of radioactivity in the eastern Massachusetts rains (in counts per minute per liter), several effects are apparent. It is shown that not only do individual detonations fail to cause equal concentrations of radioactivity in long-range fallout but also that some detonations caused no deposition in eastern Massachusetts, at least at the levels of sensitivity of these measurements. This result could be expected, since air masses over Nevada at the time of a detonation could take paths such that virtually none of the debris could be deposited in eastern Massachusetts, at least not until after circling the earth. Another effect shown in Figure 1 is that the build-up to the peak concentration of radioactivity in the fallout is much more abrupt for relatively nearby detonations (Nevada) than for distant ones (Eniwetok and the Soviet Union). Also,

six of the nineteen Nevada detonations gave higher counts per minute per liter of precipitation than either of the 1952 Eniwetok or any of the 1953 Soviet detonations. The peaks of November 15 and 29, 1953, could be from the Australian or the Siberian experiments. As with all plots measured radioactivity, the ordinate values are base -10 logarithms of the measured values. It is important that the concentrations of radioactivity in the precipitation samples were sufficiently high and the sample preparation and counting techniques used good enough that—with a single exception—no negative average net count rate of precipitation samples was obtained.

Radioactivity of Surface Waters

Below the rain concentration plot is shown the average beta radioactivity concentration in samples of surface water collected from streams and reservoirs once each week at fourteen stations. The lower of these two transverse lines connects plotted points representing the average beta radioactivity concentrations in terms of the net count rates at first counting. The first count rate per liter was made on an autoscaler, almost always three days after collection. Again, for this plot no correction was made for radioactivity decay between the time of collection and first counting, although decay measurements of all of these samples were made for other studies. Also, no correction was made for this plot for self-absorption of these samples. An error of less than 10% was introduced, because this correction was ignored. The ends of the vertical lines on this plot represent the 68% confidence zone of the mean of the statistical population from which these samples were drawn. The upper of these two transverse lines represents the upper 95% confidence limit of the mean net count rate. The concentrations of radioactivity in the surface waters were usually one to two orders of magnitude lower than those in the rain, and during one period in which there were no announced detonations (August-October, 1952), the levels fell to an arithmetic mean of about 1.16 counts per minute per liter. In both the plot of the rain count rates per liter and that of the average surface water count rate per liter, the lines connecting the plotted points are added so as better to show these changes in concentration. From the sampling and counting techniques used, it can be seen that the debris from the Nevada detonations was still detectable in the surface waters about three weeks after the end of each of the series. The increased net count rate caused by the November, 1952, Eniwetok detonations appears to have maintained the level of radioactivity in eastern Massachusetts surface waters above per-detonation values for more than two months.

Areal Concentration of Precipitation Radioactivity

The second graph from the bottom of Figure 1 shows a curve connecting plotted points representing the logarithms of the calculated daily deposition of radioactivity in units of microcuries per square mile at Cambridge. These values were obtained by multiplying the net count rates per liter of rain at first counting by the amount of rain deposited per square mile each day. The quantity of rainfall was calculated by averaging the daily measurements on the precipitation gages located at Boston's Logan International Airport, Waltham, and the Blue Hill Observatory, as reported by the United States Weather Bureau. For periods in which there were no rain, the radioactivity of the previous rainfall (in microcuries per square mile) was averaged over the entire period, including the day the rain occured. No correction was

made for natural radioactivity, self-absorption, or decay of radioactivity of the samples between collection and counting.

Areal Concentration of Runoff Radioactivity

The lowest plot on Figure 1 shows the average areal runoff of beta radioactivity in microcuries per square mile as observed for streams in the collection area. The collections for this plot were made using the surface water runoff data for the six streams--the Assa bet, Charles, Concord, Quoboag, and Ware Rivers and Kettle Brook,(formerly called the Blackstone River)--in the sample collection areas that are gaged by the United States Geological Survey. This average areal runoff value, in liters per square mile per day, was multiplied by the average count rate of samples from these same streams in counts per minute per liter and converted to microcuries. The values of the radioactivities of these streams used for this plot were the count rates per liter at the time of first counting of the samples. No correction was made for measured natural radioactivity of the streams, which probably averaged less than one count per minute per liter.

The coefficient of runoff of radioactivity is here defined as the ratio of the cumulated areal runoff of radioactivity caused by fallout as measured in the receiving streams to the areal concentration of radioactivity at the time of deposition. A rough computation of this coefficient was made using the data for the lowest curve (Figure 1) and the histogram above it. These data give an estimated overall value of the "runoff coefficient" of about 1% for fallout beta radioactivity. The results of more accurate calculations are given in Table 2 for the individual and combined streams during and following periods of high fallout radioactivity.

Rochester, New York, Area

Figure 2 shows a comparison of various radioactivity measurements conducted by other investigators in the Rochester, New York, area between 1951 and 1953. As in Figure 1, the detonation dates are shown at the top of the plate. The daily precipitations in inches at the Rochester, New York, airport are shown in the graph just below that of the announced detonations. Below the plot of detonation dates is a broken line connecting points representing the logarithms of sample fallout radioactivities, both dry and precipitation-borne, in counts per minute per 100 square feet, as measured at their first counting and plotted for the day of collection. In almost all cases the sample was measured on the day of collection or the day following. During and immediately following test periods and often in periods remote from detonations, the collection basin was rinsed with distilled water and this rinse water was processed and counted in the same fashion as the rain and snow samples. Details of the techniques used in the measurements for this figure are given in (5).

An inspection of this plot shows that the detonations at Eniwetok in 1951 raised the levels of radioactivity in the precipitation and apparently in Lake Ontario to a small extent. The first announced Soviet detonation in their test series in the fall of 1951 was registered by the increased net count rates of rain and ashed air filter samples.

It is interesting to note that in the fall of 1951 there was one fallout that caused a sample count rate (per volume of rain) more than two orders of magnitude higher than any other. To a lesser extent one fallout was dominant

over all the others that occured in eastern Massachusetts during the Nevada spring series of 1953. In the Nevada spring series of 1952 the highest concentration of fallout in rain was more than one order of magnitude above the next highest. Debris from the November, 1952, experiments at Eniwetok was detected in the precipitation. From the start of the monitoring of rain early in 1951 until April 16, 1953, the values shown are of the total beta activity. After this date the values represent the amount of beta radioactivity (in counts per minute per liter) that was retained by a Whatman No. 40 paper after filtration of the rain.

Radioactivity of Lake Ontario Water

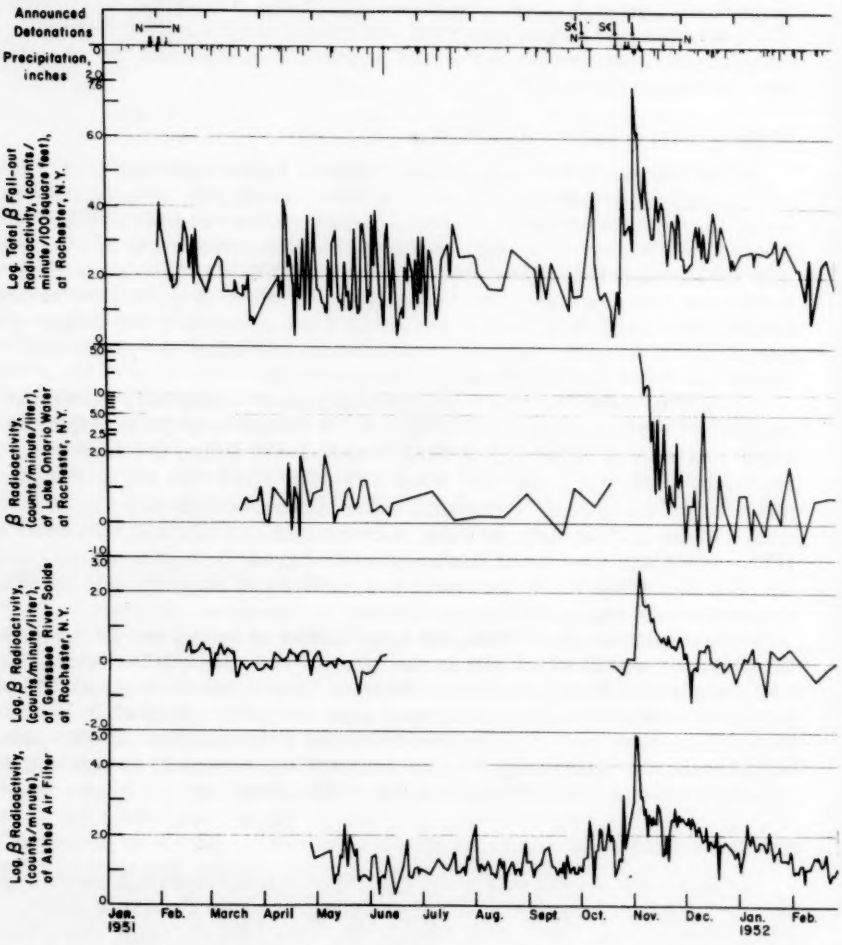
Below the plot of the areal concentration of fallout beta radioactivity is a line connecting points representing the beta radioactivity of Lake Ontario water in counts per minute per liter. During periods remote in time from detonations, the levels of radioactivity in the lake often fell to low values; with the counting techniques used, the statistical fluctuations allowed the recorded net count rate per liter occasionally to fall even to negative values. Because this curve and the one preceding it are principally for display purposes, it was decided to choose a scale arithmetic below 2.5 counts per minute per liter and logarithmic above this value.

The debris from the 1951 Eniwetok experiments apparently raised the count levels in Lake Ontario slightly. In the Nevada test the precipitation count rate peak of November 1, 1952, was followed within two days by an increase in count rate in the lake water 117-fold higher than the last reading taken before the fallout. Unfortunately, no measurements were made of the radioactivity in Lake Ontario water between mid-October and November 3, 1951. The graph shows that fission-produced gross beta radioactivity in the lake had decreased below the levels of sensitivity of measurement about a month after the end of this series.

In the spring series of 1952, the large fallout of June 4 was followed two days later by a peak count rate in the samples of Lake Ontario water. The lake samples for these measurements were taken from the treatment plant inlet that receives water directly from a pipe, the intake of which is located 1.5 miles from shore and fifty-five feet below the water surface. In this case, the mechanisms that transported the radioactivity appear to have taken about two days to cover this vertical distance of fifty-five feet.

Radioactivity of Genessee River Water

Just below the middle of Figure 2 is shown a plot connecting points representing the logarithms of the beta radioactivities in the Genessee River, which flows through Rochester, New York. The 1951 Eniwetok experiments caused little increase in these measurements, but the large deposition of November 1, 1951 and June 4, 1952, gave significant peaks. Surprisingly, the relatively large depositions in November, 1952, hardly increased the gross beta count rates above those measured before this test series. This failure in increase could be explained as the occurrence of a relatively intense local fallout at Rochester with little deposition on the watershed of the Genessee River upstream from Rochester. After March 22, 1953, the river, lake, and treatment plant samples were processed by the same techniques but in a different laboratory in the Rochester, New York, area.


Announced Detonations
N
S
Precipitation, inches
Log. Total β Fall-out Radioactivity, (counts/minute/100square feet), at Rochester, N.Y.
β Radioactivity, (counts/minute/liter), of Lake Ontario Water at Rochester, N.Y.
Log. β Radioactivity, (counts/minute/liter), of Genesee River Solids at Rochester, N.Y.
Log β Radioactivity, (counts/minute), of Ashed Air Filter
Jan. 1951
Feb.
March
April
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Jan. 1952
Feb.

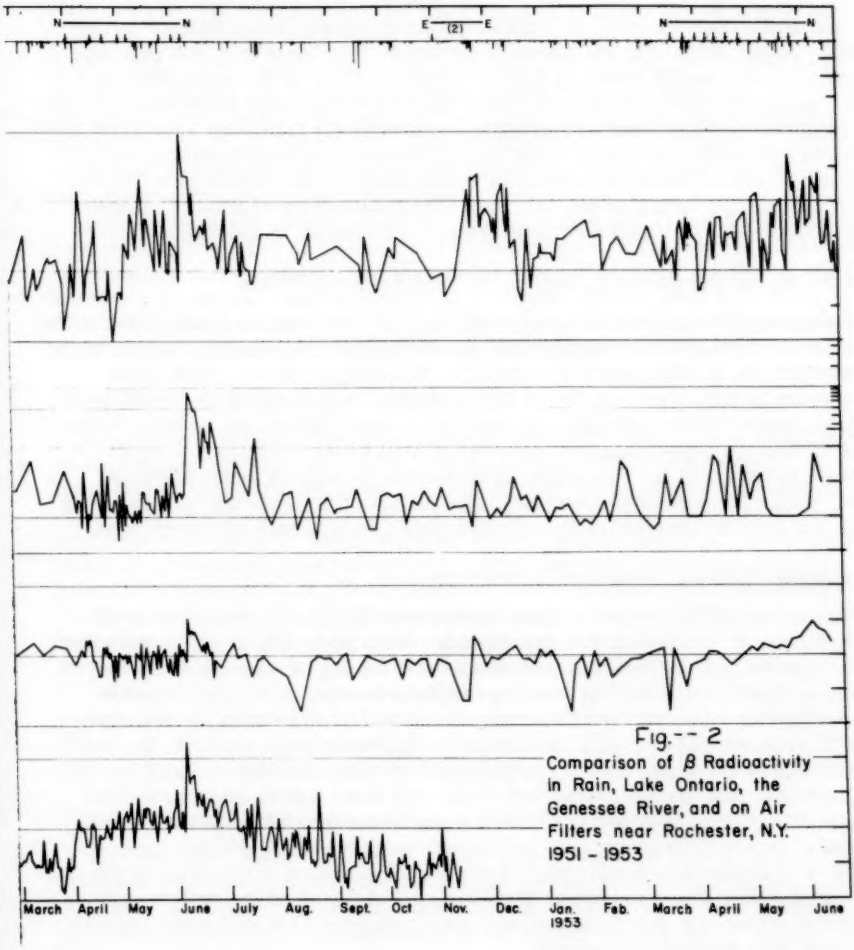


Fig.-- 2
Comparison of β Radioactivity in Rain, Lake Ontario, the Genessee River, and on Air Filters near Rochester, N.Y. 1951 - 1953

Radioactivity of Ashed Air Filters

The lowest plot on the figure connects points representing the logarithms of the net beta count rates of ashed air filters. Outside air was pulled through the thirteen-by-fifteen inch Airway filters, for from one to three days; then the filter was removed, ashed, counted, and reported as the net count rate at the first count. For cases in which air was drawn through a filter for more than one day, the measured net count rates are plotted on the median of the dates that the filters were used. It is seen that this plot indicates the same major peaks of fallout as do the plots of the rain, lake, and river samples. The fluctuations, other than those inherent in the statistics of counting, for periods neither during nor immediately following announced detonations probably are caused to a large extent by temporary increases in concentrations of naturally-occuring radon (Em^{222}) and theron (Em^{220}) and their radioactive decay products. This increased concentration of natural radioactivity can be caused by temperature inversions in the atmosphere.

Surface Water Radioactivity Due to the 1952 Eniwetok Tests

The highest average count rate reached by surface water samples from the fourteen eastern Massachusetts stations during and immediately following the Eniwetok tests in 1952 was 6.9 counts per minute per liter at first count. This value is only about six times the average of the mean of the count rates at first count of water samples at these same stations for the weekly collections in August, September, and October of that year. There were no announced detonations for more than four months preceding these Eniwetok tests. Since the date of the second experiment in this Eniwetok series is not given, no data or analysis of the surface water decay rates are presented.

Long-Range Fallout in Soil and Benthal Deposits

The spring 1953, Nevada nuclear device test series ran from March 16 through June 9. A total of 993 soil samples were collected at various depths up to eight inches on five days just before and during this period from the banks and benthal deposits at fourteen stations located throughout eastern Massachusetts. The soil samples were collected by driving eight-inch sections of commercial two-inch diameter beveled-edge steel pipe into the soil. Removal from the pipes was accomplished with a special device used by soil mechanicians that allows axtraction of the soil in as nearly an undisturbed state as practical. Sections of the soil were then used to fill planchets for automatic beta-ray counting with a thin end-window Geiger-Müller tube.

The soil samples has a lower priority on the counting schedule than the rain and surface water samples. However, all of the samples collected from any one depth on one day were counted over a short period and some interesting count-rate relations appeared.

A total of 337 samples were collected on February 21 and 28. The average counts at various depths of the bank samples and benthal samples were almost exactly the same; the surface samples gave count rates no higher than the subsurface samples. There was no indication of the November, 1952, Ivey tests debris cumulated on the soil surface.

On the 235 samples collected on March 28, (which was after the spring, 1953 test series began, although before the large fallout of April 2) the 14 benthal surface samples averaged the same count rate as the benthal

subsurface samples, but the bank surface had an average count rate about ten per cent higher than the bank subsurface samples. Even with the relatively low concentrations of antecedent fallout in the series the bank had become more radioactive than the stream bottoms. Following the large April 8 fallout, 216 samples were collected on April 13. Although the count rate of the surface benthal samples did not increase above the average subsurface count-rates, the samples taken from the top quarter inch of the bank were much more radioactive than those taken from the second quarter inch below the bank surface. The latter statement is based on the "Student" t-test between means and is true at a confidence level greater than 99.9 per cent. The top one quarter inch of bank was 60 per cent more radioactive than the quarter inch below it. There was little variation (other than statistical) in the low concentrations of radioactivity in the 92 samples taken at this time at more than one quarter inch below the surface.

The 216 bank and benthal samples collected on April 13 and the 205 samples collected on May 27 confirm the above-mentioned trends; the banks were significantly more radioactive than the stream bottoms and the fallout radioactivity was retained on the soil surface. Decay curves were run on the most active of the soil surface samples indicating that it was reasonable to assume most of the increase in radioactivity was due to the April 8 fallout.

Areal Distribution of Fallout Radioactivity

A study was made of the distribution of concentrations of radioactivity in rain samples collected at various points in eastern Massachusetts in the large fallout following the April 6, 1953, Nevada detonations. The measured count-rates were extrapolated to the time of fall, ranked, and plotted according to the procedure of Thomas[18] on logarithmic-probability paper. This plotting gave a quite satisfactory logarithmic normal distribution having a geometric mean of 1.4×10^5 counts per minute per liter and a geometric standard deviation of 6.45. This assumption was confirmed by a calculation according to Hald.[16] If the AEC maximum permissible level (5000 micro-microcuries of three-day-old total fission product radioactivity per milliliter of water can be safely consumed for any period of time[17] is accepted, a parametric calculation based on the above-mentioned distribution indicates that about 3% of a large number of rain samples taken would have exceeded the maximum permissible level. This value is thought to be somewhat low.

Time Variation of the Concentration of Radioactivity in Precipitation

Analysis was made on a single set of data given the author by Mr. B. L. Rosenthal, Lawrence Experimental Station, Mass. State Health Dept., that indicated the detonation debris is not deposited on the earth by a rainstorm in an exponentially decreasing fashion, but rather that the more intense rainfall in a storm contains the higher concentration of fission radioactivity. This observation is only tentative.

Decay of Radioactivity in Surface Waters

The same hyperbolic relationship[3] used on calculating the decrease in radioactivity in precipitation also was applied in the study of the radioactivity decay of surface water samples. In the sampling program in eastern Massachusetts from April, 1952, until July, 1953, it was found that during

each of the Nevada tests the concentration of radioactivity in the precipitation averaged approximately one hundred times the concentration in the surface waters. For the major portion of the sample collection period the count rate levels of the surface waters were so low that the naturally radioactive species and probably the long-deposited fission radioactivity interfered to an extent that no fallout decay formulation was attempted.

The fallout at the end of the Nevada series of 1952 raised the radioactivity in the surface waters of eastern Massachusetts to a level that was high enough to make possible by the techniques used an investigation of the decrease in the mean count rate on repeated measurement of the fourteen samples collected each week during the month following the fallout. Figure 3 shows the points that represent these mean count rates on repeated measurement. Although it was assumed that all of the radioactivity was formed in the detonation of June 1, 1952, it is quite probable that the samples also contained important portions of debris from other detonations. The decay curves were fitted to the plotted points by eye and terminated on their left at the times of sample collection. A curve was then drawn through those termination points to give an estimate of the rate at which the count rate decreased with time in the stream.

Decrease in Radioactivity in Surface Waters After Fallout

In the study of the decrease of radioactivity (counts per minute per liter) of streams and reservoirs, the same hyperbolic type of formulation that is used for the decay of mixed fission products was found to be practical for determining the parameters of decrease in count rate of successive samples taken on the same stream after fallout. For distinction, this parameter will be designed "m," the decrease parameter. The curves of best fit through the points representing the estimated count rates of the successive groups of samples at their time of collection are shown in Figure 3.

Selective Uptake of Fission Products in Surface Waters

As can be seen on the survey plot of the radioactivity concentrations measured for eastern Massachusetts, there were several depositions of fission debris in the spring, 1953, series that raised the levels of count rates high enough for decay study. The mixing of fission material from two or more blasts makes analysis for decay values difficult, except in the case of the April 6 detonation, which produced a fallout so large that it probably obscured the effects in the surface waters of most of the subsequent depositions from this series.

Decay parameters (n values) were obtained from the slopes of the lines of best fit as placed by eye through the plotted values of the repeated measurements of the individual samples. Table 1 summarizes these values for the surface water samples collected for three weeks following the large fallout.

Some of the relationships between the mean decay parameters of the eastern Massachusetts surface waters following the April 6, 1953 detonation were compared statistically by means of the "Student" t-test. In each case the pertinent distributions were plotted on probability paper and it was found that they were sufficiently close to arithmetic normality or logarithmic normality for distribution comparisons. At a probability level of at least 95% the following statements are true: (a) the mean of the decay parameters of the surface water samples taken on April 13 are different from the means of

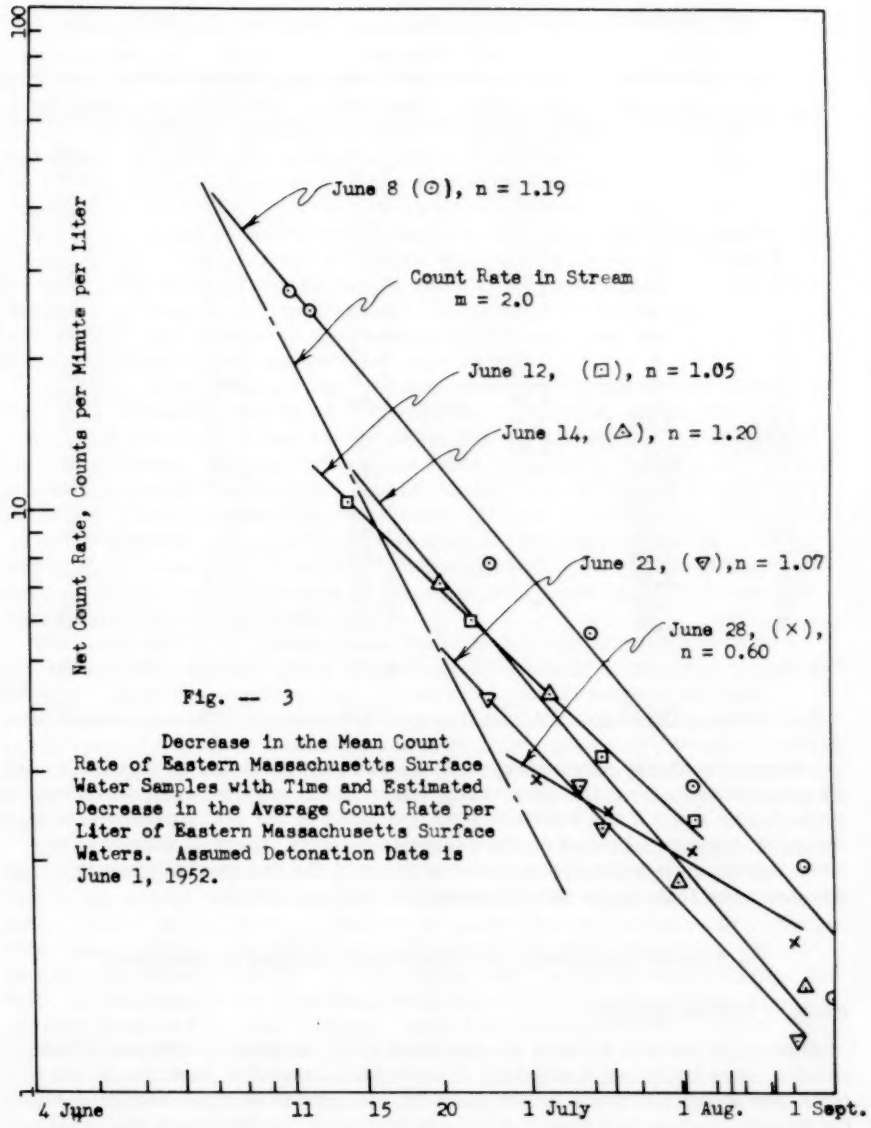


Fig. — 3

Decrease in the Mean Count Rate of Eastern Massachusetts Surface Water Samples with Time and Estimated Decrease in the Average Count Rate per Liter of Eastern Massachusetts Surface Waters. Assumed Detonation Date is June 1, 1952.

TABLE 1

DECAY PARAMETERS (n VALUES) FOR THE SURFACE WATERS OF EASTERN MASSACHUSETTS FOLLOWING THE APRIL 6, 1953, NEVADA DETONATIONS

Station	April 8	April 9	April 13	April 20	April 28
1	-	1.45	1.92	1.51	1.35
2	-	1.21	1.78	1.44	1.59
3	-	1.90	1.89	1.41	1.92
4	-	1.53	1.64	1.36	1.32
5	-	1.59	1.81	1.32	1.48
6	-	1.72	1.94	1.16	1.43
7	-	1.50	2.05	1.35	0.56
8	-	1.50	1.73	1.16	1.13
9	-	1.49	2.25	1.64	0.71
10	-	1.96	2.56	1.67	0.72
11	-	2.26	2.08	1.47	1.67
12	-	1.28	1.60	1.19	1.30
13(V)	1.49	2.01	-	1.00	1.46
14(IV)	1.55	1.52	1.78	1.05	0.92
I	1.46	-	0.92	1.65	0.98
II	1.73	-	1.54	0.97	0.90
III	1.61	-	1.03	-	0.85
VI	1.83	-	1.20	-	0.96
VIII	1.48	-	0.63	0.61	-
VII	1.59	-	1.18	0.63	0.90
IX	1.29	-	1.38	-	0.33
X	1.28	-	1.38	0.73	0.79
m n	1.53	1.61	1.62	1.23	1.10
m log n	0.133	0.208	0.113	0.098	0.010

the respective decay parameters of those samples collected on April 8, 9, and 20 and (b) the mean of the decay parameters of the surface water samples collected on April 8 and 9 differs from the mean of the decay parameters of the rain samples collected on the same dates. Thus, there is reason to believe that there is selective removal of some of the radioactive nuclear species when long-range fallout enters the surface waters.

A "Runoff Coefficient" for Long-Range Fallout Radioactivity

Eastern Massachusetts

During the Nevada tests in the spring of 1953, integrated samples of the rainfall were collected at eighteen eastern Massachusetts stations, at Harvard, and at the Lawrence Experiment Station. Seven of these sampling stations were located on streams gaged for discharge by the United States Geological Survey. As the quantity of daily rainfall is measured at many points on the collection area by the United States Weather Bureau and by the Massachusetts Department of Public Health, all of the necessary information is available for a calculation of the ratio of the total amount of radioactivity that fell on each of the seven watersheds to the total amount of radioactivity

that ran off. All but one of these calculations are based on the radioactivities of the precipitations and streams just before and for about three months after the large fallout that occurred following the April 6, 1953, Nevada detonation.

Fallout calculations for each watershed were obtained by correcting each of the one-liter rain sample net count rates for fluctuations in sensitivity of the Geiger-Müller tubes and scalers, then averaging the rates obtained from the stations of each watershed, and finally multiplying the mean count rate by the quantity of rainfall that occurred (in liters per square mile) on the watershed during the period of days the integrated rain samples were collected. The measured count rates of the three weekly sets of rain samples collected following the April 7-8 fallout were corrected to the count rates at the time of the fallout, using the decay rates obtained from the dieaway measurements of the samples. The net count rates per square mile at the time of precipitation were then summed for the period under consideration and the total count rate was converted to microcuries per square mile by the procedure given in Reference 5. The masses of the evaporated samples were usually so low that self-absorption corrections were not very large.

The count rates of the stream samples were also corrected for instrument sensitivity fluctuation and those collected during the first month after the large fallout were corrected for the decay that occurred between collection and first counting. Each of these count rates was then plotted for its collection date, a smooth curve drawn through these points and count rates thereby estimated for all days between collections. Figure 4 shows these curves for six of the streams and a curve representing the averages of the six. These curves are placed in the same figure but displaced laterally for better illustration. In each curve, the peak is placed at 3:00 hours on April 8, the estimated mean time of this large fallout.

The daily count rate values, when multiplied by the stream flow (liters per square mile per day), gave the radioactivity runoff in terms of (counts per minute) · (days per square mile). These were cumulated over the same period as the precipitation radioactivity values. All samples of evaporated residue used to measure the count rates in the streams were weighed, and the average weight for each stream was used in the conversion of the sums of runoff radioactivity to microcuries per square mile for the period of comparison.

If this sum of the radioactivity discharge values (microcuries per square mile on the day of discharge) is divided by the total radioactivity (microcuries per square mile on the day of deposition) over the same period after major fallout, an estimate is obtained for proportion of the beta-ray-omitting long-range fallout radioactivity actually appearing in the streams. This quotient the author calls the "runoff coefficient" for fallout radioactivity. It reflects retention by the watershed, self-purification by the stream, and nuclear decay in the runoff period. Table 2 summarizes these results. The high values of the coefficient for the Merrimack River in 1951 and the Assabet and Concord Rivers in 1953 could be due to imprecise measurements of the concentration of radioactivity in the precipitation of the watersheds. The geometric mean of all of these measurements in 1.2% and the median value is 0.37%. The 95% confidence limits for the true geometric mean of the coefficients are 0.27% and 5.1%.

The calculation was repeated for the same time period, using instead the mean rainfall, the mean radioactivity concentration in the rain, the mean areal discharge of the six streams, and the mean radioactivity concentrations in the

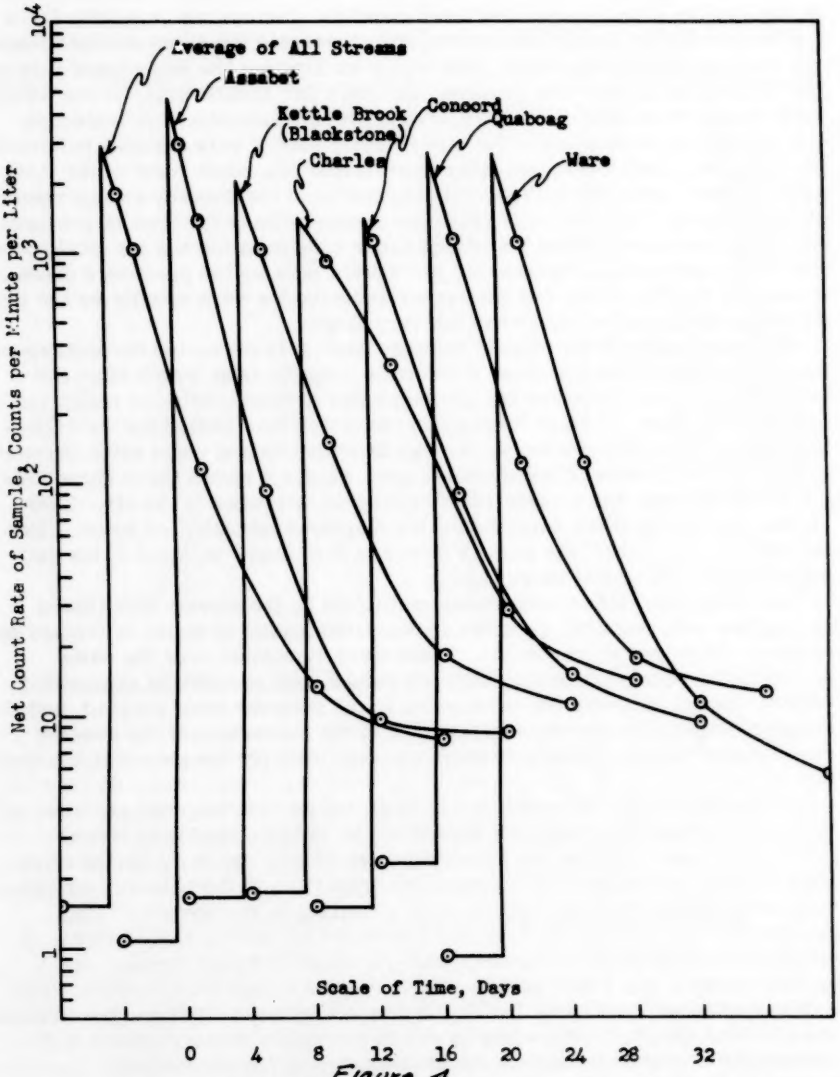


Figure 4

Radioactivity in Six Eastern Massachusetts Streams Following the April 6, 1953, Nevada Detonation. The Vertical Portion of Each Curve Represents the Time of Fallout (Approximately 38 Hours after Detonation). Curves for Streams are Separated by Displacement of Abcissa Values.

TABLE 2

"RUNOFF COEFFICIENTS" FOR GROSS BETA RADIOACTIVITY FROM EASTERN MASSACHUSETTS STREAMS

River	Time Period	Runoff Coefficient of Radioactivity
Assabet	April 1 - June 12, 1953	11.6%
Charles	April 1 - June 25, 1953	0.37%
Concord	April 1 - July 8, 1953	8.31%
Kettle Brook (Blackstone)	March 1 - July 8, 1953	1.03%
Merrimack	April 8 - May 19, 1953	0.11%
Merrimack	Oct. 28 - Nov. 26, 1951	6.26%
Ware	March 1 - July 8, 1953	0.359%
Overall calculations for the six streams	April 5 - April 28, 1953	0.43%

streams. The runoff coefficient on this basis was 0.44%. For these streams, the average water surface area is about 2.2% of the total area of the watersheds.

The more difficult problem of the runoff of the long-lived fission debris from watersheds was not investigated.

The Genessee River near Rochester, New York

The type of runoff coefficient calculation made for the eastern Massachusetts streams was also made for the Genessee River, which flows into Lake Ontario near Rochester, New York. In this case, data from only one radioactivity sampling station for the rain and one for the river water were available. Results are summarized in Table 3. The low coefficient for the period from April 1 through October 31, 1952, was due to the radioactive debris that fell on June 4, 5, and 6, amounting to 92% of the total measured for the entire period. This large fallout had little effect on the count rate of the river samples collected in this period. Local fallout at the precipitation collector, but not into the river, could account for this.

Fallout Radioactivity and the Worcester Tornado

On June 9, 1953, a cold front with attending squall line moved into eastern Massachusetts and produced the most violent tornado in the recorded history of New England, as well as one of the largest tornados ever observed in the United States. If a comparison of the location of the sample stations with the approximate path of the storm is made, it can be seen that the samples of rain and surface water collected on June 10 and 12 probably gave representative samples of the rain accompanying the tornado. Collections had been made on June 5 and 6, so that only the rains of June 7 and 8 were mixed in the samples with the fallout that occurred on June 9.

The count and decay rates of the fourteen rain samples furnish a unique opportunity to speculate on the relationship between huge tornados and

TABLE 3

"RUNOFF COEFFICIENTS" FOR GROSS BETA RADIOACTIVITY
FROM GENESSEE RIVER NEAR ROCHESTER, NEW YORK

Time Period	Number of Samples: Precipitation	Number of Samples: River	Runoff Coefficient of Radioactivity
Feb. 13 - Mar. 31, 1951	27	38	3.99%
Apr. 1 - June 11, 1951	80	33	0.92%
Oct. 16, 1951 - Mar. 31, 1952	110	66	1.43%
Apr. 1 - Oct. 17, 1952	122	114	0.057%
Nov. 1, 1952 - Mar. 17, 1953	73	37	0.562%
Mar. 18 - Apr. 16, 1953	23	7	1.54%
		Median =	1.22%
Ratio: Total Runoff Radioactivity / Total Fallout Radioactivity	435	295	

long-range carriage of fission debris. The assumption was made that the fission material originated in the June 4 detonation. The mean count rate of these samples was 157 counts per minute perliter on July 14; the mean of the decay parameters (n values) was found to be 1.12 ± 0.04. If this mean of these n values is used to extrapolate the mean count rate back to the time of deposition on June 9, a value of 1,620 counts per minute per liter is obtained. When the decay curve of the sample from Station Number 6, which had the highest count rate per liter of the group, is extrapolated back to June 9, it is seen that it then had a count rate of about 6,000 counts per minute per liter. An examination of the master plot for eastern Massachusetts (Figure 1) shown that the concentration of radioactivity in the precipitation often exceeded this value during both the 1951 and 1952 Nevada test series and that the order of magnitude of this value was reached following both the 1952 Eniwetok and 1953 Siberian experiments. The highest concentration of fallout radioactivity in rains measured at Harvard from May, 1952, until December, 1954, was that collected at Quabbin Reservoir just after the April 7-8 fallout, where the estimated count rate at the time of fallout was about 1.6×10^6 counts per minute per liter or about two hundred and seventy times that of the station that received the maximum count rate concentration during the Worcester tornado. The ratio of the means of the count rates of all the precipitation samples collected just after the April 7-8 and June 9 fallouts is $(1.4 \times 10^5) - (1.6 \times 10^3)$ or about 87. Tap samples from the city of Worchester following this tornado were measured by the usual procedure and registered only 4.1 counts per minute per liter.

In an article Comptes Rendus of 1951, M. Hubert Garrigue[19] states that soon after nuclear detonation a large part of the radioactive cloud pierces the tropopause and spreads into the stratosphere. The "Ivy" detonation at Eniwetok on November 1, 1952, sent a column of debris, coral and water ten miles into the air. The "steam" began to churn horizontally at twenty-five miles elevation to form a cloud 100 miles across. Since the Worcester tornado rose to 61,000 feet, which is well above the elevation of the tropopause, one can speculate whether or not it was able to scavenge debris from "Ivy."

It is interesting that the decay curves of several of the rain samples collected following the Worcester tornado had decay parameters (calculated with the assumption that the radioactivity was created in the June 4, 1953, detonation) considerably lower than any of those of samples collected during the large fallout of April 7-8, 1953. The decay measurements on the rain accompanying the tornado, including the one made on the June 9 Harvard rain sample 345 days after detonation, followed the hyperbolic formulation well. The lower decay parameters could not have been due to statistical errors of counting alone but could have been caused by some of the older, more slowly decaying debris from the "Ivy" detonation in the sample. Unfortunately, no chemical separations have been made on the radioactive material in these samples.

CONCLUSIONS

Based in part on samples from the National Bureau of Standards, rather extensive calibration measurements indicated a fallout beta (disintegrated)/(count rate) ratio of 2.8 u u curies per count per minute for the water samples and a ration of 2.5 for the rain samples. The average of the most radioactive set of surface water samples collected in eastern Massachusetts following November, 1952, Eniwetok detonations registered 6.9 counts per minute per liter or 0.02 u u curies per milliliter. As the peak radioactivity concentration in rain and surface waters occurred about a month after these tests, the Atomic Energy Commission—Civil Defense Administration beta concentration level for thirty day water consumption appears pertinent.(11) This indicates that for drinking water purposes, the Ivy test would have had to discharge (31,000 u u curies per milliliter)/(0.02 u u curies per milliliter) = 1,500,000 times as much fission radioactivity to reach the above mentioned level in eastern Massachusetts.

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SANITARY ENGINEERING AND REACTOR WASTE DISPOSAL[a]

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(Proc. Paper 1407)

ABSTRACT

The problem of nuclear reactor waste disposal offers a new challenge to the sanitary engineer. The general nature of reactor wastes, their effect on nature and treatment are discussed.

INTRODUCTION

The scope of this presentation will be limited to those portions of the problem of radiological contamination in the environment in which the sanitary engineer has a most direct professional interest. I will deal, therefore, with the nuclear-reactor developments and their waste potentials.

Prior to the Atomic Energy Act of 1954, the Atomic Energy Commission, in its reactor program, emphasized the production of fissionable materials, and military reactors. The new program of the AEC includes the development of several different types of power reactors. These are the pressurized-water reactor, the boiling-water reactor, the sodium-graphite reactor, the aqueous-homogenous reactor, and the fast breeder reactor.

The names given to the several types of reactors and their individual characteristics are related to the coolants and moderators and the chemical form and physical shape of their major components. However, they all have several things in common which are of principal concern to sanitary engineers.

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These are fissionable material, fission products (liquid, solid, and gaseous), coolants (liquid and gaseous), and miscellaneous sources of radioactivity.

In practice, the fissionable materials themselves do not constitute a major source of danger. They are extremely valuable and can be economically processed to almost any degree necessary for their conservation. The chemical processing operations must be geared to their conservation. However, the fission products are materials of limited usefulness in our society at the present time, although many theoretical uses are envisoned. Thus, a major interest in the environmental contamination field centers on the fission products, and the radioactivity in the coolant.(1)

Natural Radioactivity

It is true that there are waters which are naturally radioactive. However, natural radioactivity is not recognized as a limiting factor in standards for potable water even today, although possibly it should be in some instances if all the facts were known. A literature search discloses little of interest to the sanitary engineering profession in this subject until the advent of man-made radioactivity.

The radioactive background in natural waters is in the 10^{-9} to 10^{-6} uc/ml range.(2) In some radioactive springs, it may reach levels of 10^{-4} uc/ml. This background is gradually being raised by atomic detonations, and fluctuates from day to day because of many natural factors. Maximum permissible levels for some of the isotopes are within these ranges; for example:(3)

a. $Sr^{90} + Y^{90}$ 8×10^{-7} uc/ml

b. Radioactive contamination from unknown mixtures of Beta and/or gamma emitting radioisotopes in addition to natural background: 1×10^{-7} uc/ml

c. Further, for contamination affecting any population group, a limit of (1/10) of (b), or 1×10^{-8} uc/ml is applicable.

Thus, it is obvious that it is easy to confuse the background with discharges from an atomic industry. Future revisions in standards may be based upon the total exposure from artificial and natural sources, rather than from additions to background.

A similar situation applies in air. Typically the background standards for general population exposure are:

For alpha emitters	$.005 \times 10^{-10}$ uc/ml
For beta and gamma emitters	1×10^{-10} uc/ml

Radioactive Wastes Associated with Chemical Processing

Nuclear fission yields a variety of products.(5) These products, in the main radioactive, are formed in definite proportions. Fission products are produced in reactors in multimillion-curie quantities. Present practice involves extensive control measures through design and operation to confine the fission products within the reactor core and its immediate environs. The bulk of the radioactivity occurs in the form of waste only after the nuclear fuel is removed from the reactor and processed chemically to separate the valuable uranium and plutonium from the fission products in the nuclear fuel. This is being done at fuel processing plants.

At the moment, the fission-product wastes from the fuel-processing operations involve such large quantities of radioactivity that storage in special containers seems to be the method of choice. This method has several major disadvantages, such as cost, difficulties inherent in transporting large quantities of activity to a few selected sites, and continued dependence of all nuclear industries on a few Government-operated processing plants. However, it does concentrate the principal sources of radioactivity, which might contaminate the air, water, or soil, at a few processing locations.

Research is now being undertaken to find more appropriate ways of handling high-level waste from the time it is removed from the reactor to ultimate disposal. Some methods being considered are:[4]

(a) Removal and selective disposal of the more hazardous isotopes, such as Sr^{90}.

(b) Ocean disposal.

(c) Pit disposal.

(d) Subterranean disposal in deep or shallow wells and formations.

(e) Ion exchange in soils.

(f) Fixation in ceramic materials.

(g) Pyro-processing.

(h) Economical utilization of the fission products.

Each of these topics is rather broad in itself. Probably, it is most important to remember that storage is the current method of choice. Considerable effort is being expended to find more economical methods of disposal; however, these studies all involve some type of storage method.

Even though these studies are very interesting, it is the purpose of this paper to describe the impact of the more generally available types of wastes on sanitary engineering. These are the wastes associated directly with reactors.

Radioactive Wastes Directly Associated with Reactors

As mentioned above, the core of nuclear reactors contains enormous quantities of fission-product activity.[5] The bulk of this activity occurs as waste only after chemical processing. However, the corrosion of radioactive fuel elements and induced radioactive materials are factors which must be considered. A nuclear reactor produces neutrons in large numbers during the fission process. The neutrons not only maintain the fission process, but may also induce changes in the nuclei of all of the elements they contact. Thus, the operation of reactors induces radiation in both structural elements and coolants.

To minimize the environmental contamination, most reactors now under consideration have a recirculating, primary cooling system, which transfers heat from the reactor to heat exchangers. Although the primary coolant is radioactive, it does not contain enough neutron-emitting sources to effect any significant transformation of the materials in the boiler fuel, water, or steam into radioactive substances. Leakage rates of primary coolant to the steam system in the boiler are normally kept very low, so that significant quantities of radioactivity do not build up in the steam system.

Consider a typical heterogeneous reactor with solid fuel elements and a primary coolant consisting of demineralized light water. Radioactive impurities in the primary coolant will arise from:

(a) Fission products from corrosion of fuel material (resulting from defects in fuel element cladding),

(b) corrosion of core structural material which is in a region of high neutron flux and consequently has a high induced activity, and

(c) corrosion products, from the reactor cooling system, which becomes radioactive while passing through the reactor. Quantitatively, the radioactivity of these corrosion products will be proportional to corrosion rates, the probability of induced radioactivity in the corrosion products in the primary coolant system as they pass through the neutron field of the core, and the rate of purification of primary coolant.

Thus, production of radioactivity in the materials which are discharged to the environment is minimized, but arrangements to handle radioactive contamination are nevertheless essential. The increase in activity in the coolants not only creates a waste problem, but may also create an external radiation exposure hazard for the operating and maintenance personnel. Therefore, present practice requires consideration of continuous removal of the fission and corrosion products through demineralizers. This moves the waste materials to another system, and concentrates the activity but does not really provide a waste disposal method.

The large variables in estimated design quantities are the rates of corrosion and the probability of core element failure. Even though these may be subject to considerable fluctuation, the radioactivity involved in the resultant waste is only a small fraction of the total activity remaining in the core. However, even though these wastes are in the microcurie concentration range, they will require processing in most instances, to assure average radioactive concentration levels of 1/10 the current National Bureau of Standards Handbook values: for example, 1×10^{-8} uc/cc for unknown mixtures of isotopes, affecting the general population.

On a day-to-day basis, there are also wastes from the laboratory, laundry, and decontamination operations which must be considered.

For wastes in the 1×10^{-4} uc/ml range, temporary storage may be adequate to reduce the activity to a level where the available dilution water will reduce it to less than the maximum permissible concentration. Other types of waste may be sufficiently concentrated that they may justifiably be placed directly in ultimate-disposal storage tanks. The intermediate concentrations in the 20-200 uc/ml range are generally too radioactive to handle through temporary storage and direct disposal into the environment. Conversely, they are sufficiently bulky that it is generally economical to concentrate them by means of temporary storage and ion exchange, or evaporation before they are placed in ultimate storage.

Details on the wastes will be presented on a case basis at the end of this paper.

Standards

The National Committee on Radiation Protection, in Handbook 61, has

recommended isotopic standards for radioactivity in water and air for occupational exposure.[3]

This handbook also contains mathematical expressions which enable one to calculate a criterion for waters which contain more than one radioactive isotope.

Typical recommended standards in terms of uc/ml of water are:

Rn^{222} + daughters	2×10^{-6}
Ra^{226} + 1/2 daughters	4×10^{-8}
Pu^{239} (sol)	1.5×10^{-6}
K^{42}	1×10^{-2}
I^{131}	3.0×10^{-5}
Sr^{89}	7.0×10^{-5}
Sr^{90} + Y^{90}	8×10^{-7}
Radioactive contamination from unknown mixtures of β and/or γ emitting radio-isotopes in addition to natural background	10^{-7}

It is readily apparent, by comparing these numbers, that many of the standards for the individual isotopes and mixed fission products are close to the natural radioactive background of 10^{-9} to 10^{-6} uc/ml. A comparison of these standards with the Public Health Service Drinking Water Standards is shown in Table I.[6]

In addition to these standards, the current drafts of the AEC health and safety regulations, as well as the NCRP model State regulations, require that public drinking water standards be established at 1/10 the values recommended by Handbook 61. This factor has been inserted primarily because the detrimental genetic effects of radiation probably increase with an increase in the numbers of people exposed.

Use of Standards to Determine Health Criteria

However, to protect the public and to assist in the development of the atomic-energy industry, sound practices in related area must be developed and generally understood by those responsible for design, operation, and regulation of the industry.

The standards do not tell how much of a given radioactive mixture can be discharged into a river. There are questions of the point at which the measurements might be made, how many samples should be taken, how they should be analyzed, averaged, reported, and evaluated.

Let's discuss for a moment, the question of sampling points, as it is currently being considered.

In June of 1954, the AEC and public-health officials discussed a policy for its principal contractors which was based upon the average concentration in water at points of supply (exclusive of treatment, if any) prior to use by humans.

The current draft standards for protection against radiation for AEC licensees follows a different pattern, which is probably more acceptable to stream pollution control officials.

(1) Generally, discharge beyond the effective control of the licensee must comply with 10 percent of the Maximum Permissible Concentrations recommended by the NCRP.

(2) Exception will be considered, if the concentration of radioactive material in water before treatment (if any) at points of regular supply to individuals, or to domestic animals used for food, or in edible plants, is not likely to exceed 10 percent of the Maximum Concentration recommended by NCRP.

It is apparent from the approach that has been taken to this one problem that the AEC intends to prevent the discharge of health-significant quantities into waterways. However, a stringent approach could lead to expensive treatment and confinement techniques which will eventually influence the investor or manager who balances the cost of nuclear power against conventional fuels. Therefore, regulatory agencies charged with protecting streams must also be reasonable in their choice of sampling points as well as in the use of standards used to check the compliance of the industry. Standards of this magnitude present a measurement problem to industry, health agencies, and their designers, because they are within the range of natural radioactivity.

Another concept which is basic to the regulation of radioactivity in water is the concept of averaging results over periods of several weeks. This is scientifically sound when one is dealing with radioactivity at low levels because the reaction of the body at such levels is dependent upon the total activity assimilated, rather than upon the rate of assimilation. Generally, periods of 13 weeks are being considered as units for averaging the concentrations.

Methods of Assessment

Another gap in our sanitary engineering techniques results from the lack of standardized and reliable methods for radiation assessment. Methods for assay of radioactivity in water have been developed to provide procedures for determining the appropriate gross activity of waters at levels as low as 10^{-8} microcuries per milliliter (uc/ml). Measurements of activities of this order of magnitude or lower are needed to determine the natural background radioactivity in waters and to detect increases in activity before they reach levels which would interfere with use of the water for industrial or domestic purposes.

Since no instrument currently available is capable of measuring activities of this level in water directly, some method of concentrating the activity is required. The method ordinarily used is evaporation. Radioactive gases and volatile substances will be lost in evaporation, iodine may be lost if present in elemental form, and isotopes with short half-lives may die out during sample preparation. With these limitations most methods give a reasonably good measurement of total activity providing the solids content of the water is not too great. For determination of the activity due to specific elements more elaborate techniques are required.

Assay methods for air involve both the radioactivity that may be associated with gases, such as Xenon and Krypton, or with particulate matter. The methods for measuring the radioactivity associated with particulate matter in air, at levels well below those stated as the maximum permissible, are

fairly well worked out, and lend themselves to the use of a variety of radiation counting apparatus. In general, the particulates are concentrated by passing large air volumes through a retaining medium, such as a filter. Portions, or all, of the filter material, which may be further prepared chemically or physically, are examined quantitatively for the various radiations expected, and assayed on the basis of comparison with known standards. Either gross radioactivity, or specific radio-contaminants, may be identified.

Radioactive gases cannot readily be concentrated from the air for assay, and therefore have to be measured at points where the activity and concentration are high, such as in the stack, or at the last point of storage. The principal sources of such gases are nuclear reactor operations and nuclear spent fuel processing.

In order that official health agencies, at a minimum expense and with optimum utilization of available staff, may be guided in radiation assessment for investigative and control purposes, it is planned to increase efforts to develop a choice of standard sanitary engineering techniques for radiation assessment which are capable of interpretation and reporting in a uniform manner, much the same as the existing "Standard Methods for the Examination of Water and Sewage." This will include the development of sampling methods (number, types, sizes, locations, frequencies) meeting statistical and other requirements for reliability and significance, and development of standardized analytical methods. Related to this will be the development of sanitary engineering indices of radioactive quality to reduce cost and complexity of the procedures. This would include such things as the use of single isotopes as indicators of complex mixtures of radioactive materials, the use of selective biological samples as indicators of radioactive buildup, and the employment of selective chemical samples as indicators of complex radioactive buildup. The use of these procedures will require, also, development of uniform reporting procedures and evaluation of results, in order that they may be interpreted in terms of public health significance.

Effects of Water-Treatment Processes on Radioactive Wastes[7]

The effects of normal water-treatment processes on radioactive liquids has been studied by the Public Health Service and other Federal agencies. These processes have been found to remove some radioactivity, but they do not remove sufficiently significant amounts of cesium and strontium, the critical isotopes, to justify reliance upon waterworks processes as a protective factor. It appears that waterworks should make every reasonable effort to know the radioactive levels in their sources, through measurement and collaboration with the atomic-energy industry, and should protect their works through this intelligence, auxiliary supplies, and emergency storage.

Effects of the Natural Environment

Sanitary engineers have uniquely utilized the natural biological, chemical, and physical properties of the environment to protect populations from the effects of pollution. The limited amount of work that has been done indicates that environmental properties can be utilized to protect populations against radioactive discharges, through retention of the materials at locations inaccessible to human use until radioactive decay processes have reduced the hazard to acceptable levels, and through dilution to acceptable levels at the first point of human contact. Conversely, these same properties may serve

to reconcentrate radioactivity to such an extent that hazardous conditions are created. In order that sanitary engineering criteria governing site selection and waste disposal may be based on realistic and economic safety factors, additional research must be performed to measure the usefulness of each natural process with either assists or detracts from environmental waste-disposal methods. This research will need to include studies on waste characteristics, natural dispersion, and natural retention. This type of research can best be undertaken jointly by industrial and health organizations.(4)

Regulations

The Atomic Energy Act of 1954 defines the Commission's primary responsibility as the defense of the national security through the development, manufacture, and testing of weapons, as well as the ownership and control of all fissionable material. Beyond this, the Commission was authorized to invite American industry into a closer cooperation with the Government for the development of atomic energy for the public good. The 1954 Act marked a transition from a statutory Government monoply to a regulated, free-enterprise industry. As a portion of its responsibility, the Commission is obliged to provide for the safety of the operations which it authorizes, and to prevent public harm from resulting. The Commission, however, is specifically enjoined from setting itself up in the nuclear power business. In the process of licensing private power reactor operation, the direct responsibility for occupational and environmental radiological health control is placed upon the licensee.

There is now a pattern developing in the relationships between the Government-sponsored nuclear-energy industry and the State agencies. It is urgently desired that the industry be supplied with design and operational health and safety criteria which permit the least restrictions on economy of operation. These, in part, will be furnished by the "Proposed AEC Standards for Protection against Radiation," which will establish the maximum operating levels which are acceptable to the AEC.

The State health agencies, which have a much broader concept of radiological health, are concerned with the total radiation exposures of the States' populations, no matter what the sources of exposure might be. At the present time, for example, the principal sources of exposure to radiation of a generalized community are, probably, natural background radiation and diagnostic x-ray. Health agencies, as they conceive their duties, desire to maintain public exposures at the minimum obtainable, and to admit additional sources of radiation principally when it is demonstrable that little increase is anticipated, and that the possibility of individual hazard is minimized by adequate control procedures.

A convenient analogy may be drawn at this point. An industrial waste treatment plant, if proposing to discharge its final effluent into a potable water supply, is generally not required to upgrade its effluent to meet drinking water standards. Instead, through the assistance of experienced design engineers and consultants, and with the cooperative guidance of the responsible State authorities, a degree of control for the effluent is decided upon which by making use of all natural or manmade site factors that exert a protective influence, provides a reasonable expectation that undesirable levels will never be reached. Effective water-treatment methods, for example, may provide all protection that is necessary, an additional factor which cannot be

relied on when dealing with radioactive wastes. The entire procedure is also "backed up" by policing and enforcement powers within the State's jurisdiction, but undoubtedly both parties look upon this only as a final resort. We may assume that identical procedures will be effective in establishing desirable environmental relationships between nuclear industries and their surrounding populaces. Although the terminology and scientific methods may be new to some, the administrative processes need not be very different.

An Example

Rather than discuss the principal sanitary engineering considerations in further detail, let us consider a specific case, the Pressurized Water Reactor being constructed by Westinghouse and Duquesne at Shippingport, Pennsylvania, under the direction of the AEC.[9, 10]

In this instance, the site and type of reactor were selected largely on the basis of nonsanitary-engineering factors. The problem resolved itself into adapting the calculated hazards to meet the environmental health standards. These in turn may be divided into two categories: the improbable, accident, and normal radioactive discharges. The former will be handled largely by core design and controls, a sealed, steel enclosure, and the distances and hills between the plant and population centers.

The wastes which accumulate on a day-to-day basis are the principal sources of sanitary engineering design interest.

It was decided to design to try to meet the 10 percent of the NCRP standards at the point of discharge, in addition to natural background. This immediately introduced several major determinations, i.e., natural background, probable wastes, and methods of treatment.

Radiological background studies were initiated in the immediate environs of the reactor by the Westinghouse Electric Company and the Dequesne Light Company, under the guidance of the Pittsburgh Operations Office of AEC. Through the cooperative action of the Ohio River Valley States, the Ohio River Valley Sanitary Commission, and the Public Health Service, a radiological survey was initiated throughout the length of the stream. The local samples and those collected at more distant points and other laboratories are being cross-checked to assure uniformity.

At this time, the survey is still under way, but we have every reason to believe that an agreeable radiological baseline will be established by the time reactor operations begin.

The next step undertaken by the company was a determination of the quantities and types of wastes which could be expected. This involved many calculations, tests, and analyses of data. The summary presented in the following paragraphs and illustrations is based upon data prepared at the request of the authors by the Westinghouse Electric Company and the Naval Reactors Branch of the AEC.

It is anticipated that the total activities to be disposed of will be as follows:

Solid	3.4×10^8 uc. day (average)
Liquid	4.86×10^6 uc/day
Cases	2.1×10^7 uc/day

The design limits on activity levels at the point of discharge from the controlled area (i.e., at the top of the stack and at the entrance to the Ohio River)

are 1×10^{-8} uc/ml for liquids and 1×10^{-7} uc/ml for gaseous wastes, Krypton^{85} and Xenon^{133}.

Summaries of the quantities and activities of five (5) of the eight (8) types of the wastes before and after treatment, and before and after dilution, are shown in the attached tables, Tables IIa, IIb, IIc and IId. The other types are combustible waste which is expected to have a low but variable radioactive content, and non-combustible waste. The combustible waste will be incinerated and the ash slurry will be placed in the spent resin storage. Small non-combustible items will be shipped via railroad or truck for ocean burial. The large items will be buried at the site.

The overall calculated results, which appear to be reasonable and conservative, can be checked at the points of discharge. The calculated average radioactive discharge per day with the condenser water will be 3.16 millicuries. Better knowledge for future design and regulatory purposes will thus become available, and operating anomalies, such as surges in activity, can be controlled by allowing additional storage time in each of the treatment systems.

Thus, at this time, it appears that reactors can be designed to meet the health standards established for radioactivity in the environment. However, work on the assessment of the design and the development of more economical treatment methods must continue, and must probably be worked out for each individual type of reactor.

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TABLE I

Comparison of Some Chemical Standards in Current Public Health Service "Drinking Water Standards" and Maximum Permissible Concentrations of Radioisotopes in Water

	Drinking-water standards		Maximum permissible radioactive concentrations		Radioactive form
	p.p.m. (mg/l)	ug/cc	ug/cc	uc/cc	
Grounds for rejection					
Lead (Pb)	0.1	0.1	3.1×10^{-7}	0.1	Pb^{203}
Fluoride (F)	1.5	1.5	9.7×10^{-9}	0.9	F^{18}
Arsenic (As)	0.05	0.05	1.3×10^{-7}	0.2	As^{76}
Recommended values					
Copper (Cu)	3.0	3.0	2.1×10^{-8}	8×10^{-2}	Cu^{64}
Iron & Manganese (Fe & Mn)	0.3	0.3	1.8×10^{-6}	4×10^{-3}	Fe^{55}
			2.1×10^{-9}	1×10^{-4}	Fe^{59}
			6.9×10^{-9}	0.15	Mn^{56}
Chloride (Cl)	250	250	8.9×10^{-2}	2×10^{-3}	Cl^{36}
Sulphate (So_4)	250	83 (S)	1.2×10^{-7}	5×10^{-3}	S^{35}
Phenolic compounds (C_6 H_5 OH)*	0.001	1.3×10^{-4} (1 atom c)	6.7×10^{-4}	3×10^{-3}	C^{14}

*It is assumed that only 1 atom of carbon is radioactive.

TABLE IIa

REACTOR PLANT SYSTEM SPENT RESIN

Type Waste	Source	Volume	Average Concentration of Radioactivity	Treatment Process	Total Activity Before Treatment	Total Activity After Treatment	Ultimate Destination
Reactor plant system spent resin	Decontamination of: a) Coolant purification (fuel element rupture detection system) b) Canal system c) Hot laboratory wastes	36 ft^3 per month	10^4 uc/cc (maximum)	Storage	10^{10} uc/month	varies as a function of holding time and decay	solid phase--land storage. Liquid phase--to holding tanks

TABLE IIb

SOLID WASTES OTHER THAN ION EXCHANGE RESIN

Type of Waste	Volume	Concentration of Radioactivity	Treatment Process	Total Activity Before Treatment	Total Activity After Treatment	Ultimate Destination
Combustible	10,000 - 20,000 lb/month	Variable but low	Incineration (gases scrubbed and filtered)	Variable		Ashes and wash water slurried to storage.
Non-combustible						
Small items	unknown	Variable but low	sealed in drums	Variable		Ocean burial
Large items	unknown	Variable but low	underground storage	Variable		"graveyard" burial

TABLE IIc

LIQUID WASTES FOR AN AVERAGE DAY

Source	Quantity	Activity Prior to Dilution	Treatment Process	Activity After Treatment	Activity After Dilution	Ultimate Destination
Cold laundry and monitored drains	5630 gal/day	1×10^{-6} uc/cc	Temporary storage and dilution with condenser	Varies with hold time and dilution	1×10^{-8} uc/cc	Ohio River
Hot laundry and special monitored drains	2950 gal/day	1.1×10^{-4} uc/cc	Temporary storage and dilution with condenser	Varies with hold time and dilution	1×10^{-8} uc/cc	Ohio River
Treated decontamination room waste	250 gal/day	0.27 uc/cc	Distillation --effluent to temporary storage before dilution	2.7×10^{-7} uc/cc	1×10^{-8} uc/cc	Diluted effluent to Ohio River Sludge to underground storage
Treated reactor plant effluent	467 gal/day	7.6 uc/cc	Ion exchange effluent to temporary storage before dilution	2.4×10^{-4} uc/cc	1×10^{-8} uc/cc	Diluted effluent to Ohio River. Resin to burial

TABLE II(d)

VOLATILE WASTES

Source	Quantity	Activity Prior to Treatment	Treatment - Process Steps	Activity After Treatment	Ultimate Destination
In solution reactor effluent	467 gpd	Volatile component: 7.6 uc/cc	1. 45-day hold in surge and decay tanks	Volatile component: 2.7×10^{-2} uc/cc	
Removed from solution by gas stripper	0.015 cfm	2.7×10^{-2} uc/cc	2. 60-day hold in gas decay drums	2.7×10^{-5} uc/cc	
			3. Dilution with 9000 cfm of air	Less than 1×10^{-7} uc/cc	
			4. Atmospheric dispersion through stack	Less than 10^{-12} uc/cc	

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DISPERSAL OF POLLUTION BY TIDAL MOVEMENTS[a]

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(Proc. Paper 1408)

ABSTRACT

The disposal of sewage into tidal waters has created many problems for the sanitary engineer. Chief among these is the calculation of total load which can be placed upon the tidal waters. A method of approach to this problem is given with data on the Potomac River and the Delaware River.

SYNOPSIS

In portions of streams where tides cause substantial flow reversals, pollution assimilation capacity is greatly increased due to wide dispersal and mixing over large areas. The net downstream movement due to stream flow and the magnitude of the stream flow, in such cases, may be of relatively minor effect. Following a description of tide movements, calculations of the tidal prism, and the way in which entering pollution is dispersed, with some mention of the difficulties of applying oxygen balance computations to tidal waters, data are presented on the physical characteristics of the Delaware River at Philadelphia and the Potomac River at Washington. Results of stream surveys of these rivers are given, including actual relationships between pollution loads and depletions of dissolved oxygen at various stream flows.

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a. Presented at a meeting of the American Society of Civil Engineers in Pittsburgh, Pa., October 15, 1956.

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INTRODUCTION

Where a river meets tidewater it enters a transition area in which its characteristics change from those of a uniformly flowing stream to those of a shifting body of water which follows the tide cycle in its movements from and toward the sea. The purpose of this paper is to describe generally the physical and hydraulic characteristics of the transition portions of tidal rivers and to discuss briefly the effect of such characteristics on the ability of the waters to assimilate pollution loads.

In stream pollution studies, a basic problem is the determination of the capacity of the receiving waterway to assimilate pollution. When this is known, the required degree of treatment for any present or future raw sewage load is also known. A secondary problem may be the determination of the actual value of low flow augmentation in the improvement of river conditions or the saving in sewage treatment costs.

The methods commonly used in estimating or calculating the self purification ability of uniformly flowing streams unaffected by tides apparently are not applicable to tidal waters. They certainly cannot be applied realistically on the assumption that tide movements can be ignored. Attempts to apply such methods have resulted in calculated capacities that were much lower for the lowest stream flows and higher for the higher stream flows than are borne out by the records of actual stream surveys.

A number of past studies and calculations on tidal portions of rivers have failed to take into account or give proper weight to the effect of wide dispersal due to tidal movements. Too much stress has been placed on the stream flow, which actually may be an exceedingly minor factor. In waters of this nature, it is doubtful that low flow augmentation within feasible limits can improve materially the capacity of the stream to assimilate pollution or permit any major reduction in treatment requirements.

Relation Between Tidal Movements and Stream Flow

The tidal prism at any point is the water between the high tide and low tide water surfaces upstream from that point. Its volume is the product of the surface area of the stream between the point and the head of tidewater multiplied by the difference in elevation between high tide and low tide.

The range of tide levels is different at different places and varies not only with the seasons but also with weather conditions. The time period of the tide cycle is 12.4 hours.

Starting at low tide, the tidal prism volume is filled during the first half of the cycle, about 6.2 hours, and emptied during the second half of the cycle. To the extent available, the volume is supplied by the natural flow from upstream. The remainder of the volume is supplied from downstream. Assuming that the tide levels change in accordance with the sine curve, the rates of filling or emptying the tidal prism will vary from zero at the times of high and low tides to $\frac{\pi}{12.4}$ times the volume of the prism as the maximum rate per hour.

Wherever the natural stream flow is less than this maximum rate, reversal of flow at some time during the filling portion of the cycle may be expected. Except for points very close to the head of tidewater, it is likely that substantial flow reversal takes place except during the very high stream

flows. With the outgoing tide, the volume of water flowing downstream past the point is equal to the volume of the tidal prism plus the volume of natural stream flow during the ebb period.

The maximum rates of flow, upstream and downstream, past any point may be many times the natural flow rate, and may be sufficient to effect a considerable scouring action. Also, the tidal movements promote relatively thorough mixing and turnover, particularly after several tide cycles.

The mean low water volumes of the tidal portions of a river from the head of tidewater to various points downstream may be calculated from the depths shown on government navigation charts. Volumes of tidal prisms may be estimated from the tide elevation data appearing on the charts. For study purposes, mass curves of the volumes are convenient. An example, for the Potomac River at Washington, is shown on Figure 1.

Using such curves, calculations may be made of the distances of upstream and downstream travel throughout the tide cycle for various rates of natural stream flow. Such calculations do not take into account the unequal velocity distribution known to occur, and to this extent give results that are theoretical only. Actually, portions of the moving body of water will travel greater or lesser distances at greater or lesser velocities.

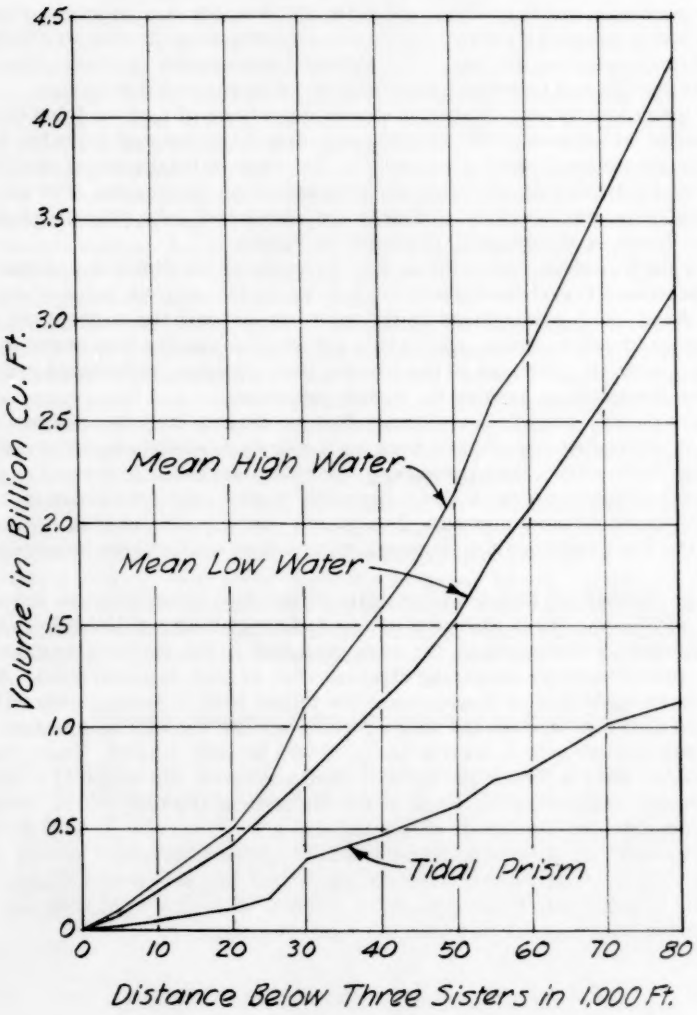
Sewage discharged into a uniformly flowing stream may be assumed to occupy an expanding egg-shaped area as it moves downstream, ultimately becoming thoroughly mixed throughout the cross-section. In a rapidly moving stream of small cross-section, thorough mixing may take place in a matter of hours or even minutes. In a slowly moving stream of large cross-section the time required for thorough mixing may conceivably be several days.

Sewage discharged into a tidal stream where flow reversals are substantial will have a much different pattern. At high tide and low tide, with no flow upstream or downstream, the area occupied by the entering sewage will closely approximate an expanding circular disc of high concentration. As the water moves upstream or downstream the initial bulb of sewage also will move, and half way through the flow or ebb when the velocity is greatest the sewage will occupy only a narrow area, or will be well diluted. Thus, the fresh sewage after a 6 hour period will have somewhat the shape of a dumb-bell, of length approximately equal to the distance of the tide travel, with a bulb of concentrated sewage at either end and a long, narrow or well diluted area in the middle. Although after a few tide cycles substantial mixing and dispersal will have occurred, it seems likely that this dumb-bell shaped concentration of relatively fresh sewage or effluent will exist at almost any time, moving upstream or downstream past the outlet.

Pollution Loads and Assimilation Processes

Studies of the capacity of a stream to assimilate pollution are concerned principally with the desired residual dissolved oxygen and with the oxygen demands of treated or untreated sewage discharged to the stream. These demands can be estimated from knowledge of the quantities and characteristics of the sewage. Other demands about which less is known include those present in the incoming stream, the demands of bottom deposits, storm overflows from combined sewers, storm drainage and direct surface runoff, and the oxygen requirements of living plant and animal matter. Such demands may be subject to extreme variation.

FIG. 1



POTOMAC RIVER AT WASHINGTON
RIVER VOLUMES

Even knowledge of the demands of the sewage in many cases is limited to laboratory determinations of the 5-day 20° B.O.D. and the rates at which the first stage demands are exerted. In cases where the time of travel to and beyond the critical portion of a stream as regards oxygen depletion is not over 8 to 10 days, such determinations may be an adequate basis for oxygen balance calculations, but where the time of travel through the affected reach of a stream is much greater, as may be the case in tidal portions of rivers, needed information on the demands through the second stage and on the long time total demand of a particular sewage or waste is usually not available. Little is usually known about the rates of exertion of the demands of the incoming stream, bottom deposits, storm runoff and the like.

Oxygen to meet the demands is supplied from the air, through the exposed water surface, and from other sources, including the dissolved oxygen in the incoming stream and in the sewage itself, and oxygen supplied by green plants. Vegetation alternately exposed and submerged in tidal flats and marshes may aid materially in supplying oxygen to the water through the entrainment of air. Many uncertainties and unknowns that affect the quantities and rates of availability of oxygen from the several sources include such variable influences as stream flow, wind velocity and direction, tidal movements, temperature, sunlight and rainfall. About the only thing that appears to be definite is that the rate of absorption of atmospheric oxygen through the water surface is proportional to the depletion of dissolved oxygen below saturation.

Tidal movements promote favorable conditions for the absorption of atmospheric oxygen by spreading of the polluted waters over a large area and by high velocity mixing.

Examples—Physical Characteristics

Examples of the tidal portions of rivers which receive large pollution loads and which have been studied to determine their assimilation capacities at various stream flows are the Delaware River at Philadelphia and the Potomac River at Washington. The writer's firm has been engaged on sewage disposal projects by Philadelphia and by the District of Columbia, and at both places competent river surveys have been made.

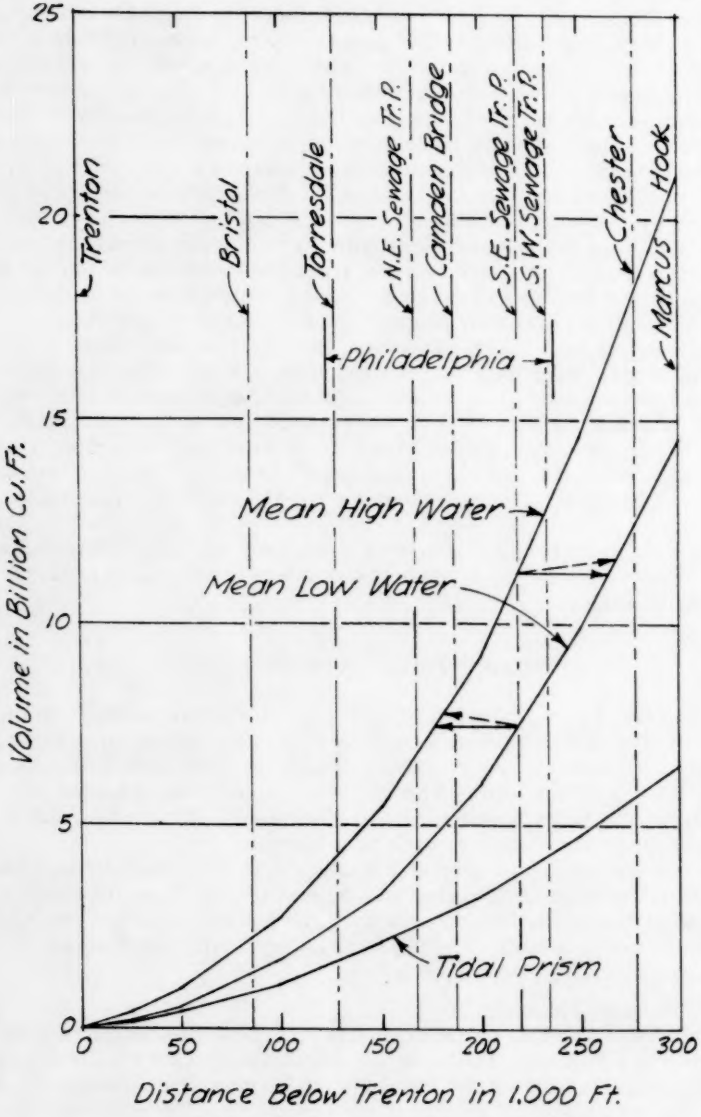
Tidal movements are greater at Philadelphia than at Washington, as for the Delaware the head of tidewater is at Trenton, some 25 miles above Philadelphia, whereas for the Potomac the head of tidewater is within the limits of the District of Columbia. The physical and hydraulic characteristics of the two streams are briefly described below.

Delaware River at Philadelphia

The Delaware River at Philadelphia has an average discharge of about 12,000 cfs and a minimum discharge somewhat under 1,500 cfs. The mean range of tide levels is about 5.4 feet. Figure 2 shows river and tidal prism volumes for the upper tidal portion of the stream from Trenton to Marcus Hook, a distance of 57 miles.

At zero natural stream flow, upstream and downstream movements during rising and falling tide levels would be the horizontal distances between the low water and high water curves at points of equal volume. At one selected location, for example, the upstream and downstream movement would be from 8 to 8 1/2 miles in either direction. With natural stream flow, the upstream

FIG. 2



DELAWARE RIVER AT PHILADELPHIA

RIVER VOLUMES

movement will be less and the downstream movement greater, the volumes being modified approximately by the stream flow volume in a 6.2 hour period. In this case, with a flow of 10,000 cfs, the movements would be about half a mile less upstream and greater downstream. The tidal movements thus are not greatly affected by the lower stream flows.

The time of travel at, for example, 4,000 cfs, is about 21 days between the Philadelphia limits, with an average rate of movement of about 4,000 feet per day or less than 3 feet per minute. In comparison, the upstream and downstream movements of water during the tide cycle are more than 40,000 feet in 6.2 hours, reach a maximum rate of approximately 250,000 cfs, and have a maximum calculated velocity of more than 3 feet per second.

The surface area exposed by one day's travel at 4,000 cfs would be about 350 acres. In comparison more than 10 times this area is exposed during the movements of each tide cycle.

Potomac River at Washington

The Potomac River at Washington has an average flow of about 11,000 cfs and a minimum flow under 800 cfs. The range of tides averages about 2.8 feet. River volumes for the 80,000 foot reach from the head of tidewater to Fort Washington have been shown on Figure 1. Figure 3 shows the volumes for the portion of the river immediately above and below the D. C. sewage treatment plant outlet. For zero stream flow, the upstream and downstream movements would each be about 10,000 feet during incoming and outgoing tides. Combined with a stream flow of 10,000 cfs, the distances would be about 5,000 feet upstream and 16,000 feet downstream.

The time of travel at 2,000 cfs is about 7 days from the head of tidewater to the treatment plant outlet and about 13 days from the outlet to Fort Washington. At this flow, the velocity past the outlet is less than 3 feet per minute. In comparison, the movement during the tide cycle reaches a maximum rate of approximately 33,000 cfs, with a computed maximum velocity of 44 feet per minute or 0.73 feet per second.

The surface area exposed by one day's travel at 2,000 cfs would be about 460 acres. In comparison, the computed surface area exposed during each tide cycle is from 900 to 1,400 acres. Irregularities in velocity distribution will cause the actual spread after a few tide cycles to be much greater. This effect is illustrated by Figure 4.

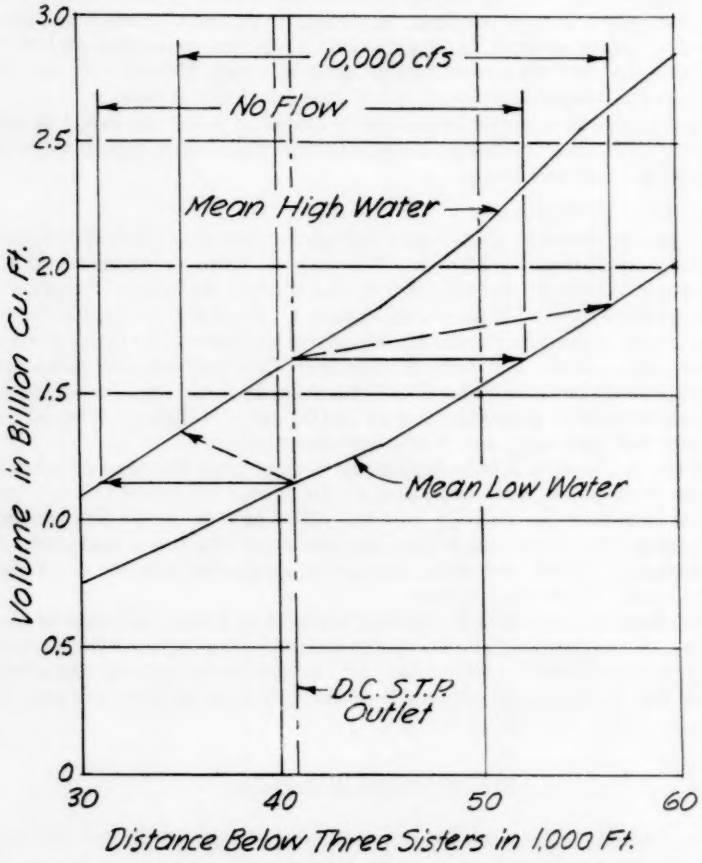
Results of Stream Surveys

Stream surveys of both the Delaware River at Philadelphia and the Potomac River at Washington have been made to determine the actual conditions of the rivers under past and present pollution loads. The surveys and their results are briefly described below.

Delaware River at Philadelphia

Of many river survey runs conducted in recent years by the City of Philadelphia on the Delaware River, those covering warm water periods from August, 1949, to October, 1951, are discussed herein. The range of river discharges during and preceding the sampling runs was from below 3,000 cfs to more than 9,000 cfs. Much of the material presented dealing with the interpretation of the results of these surveys was obtained during studies of

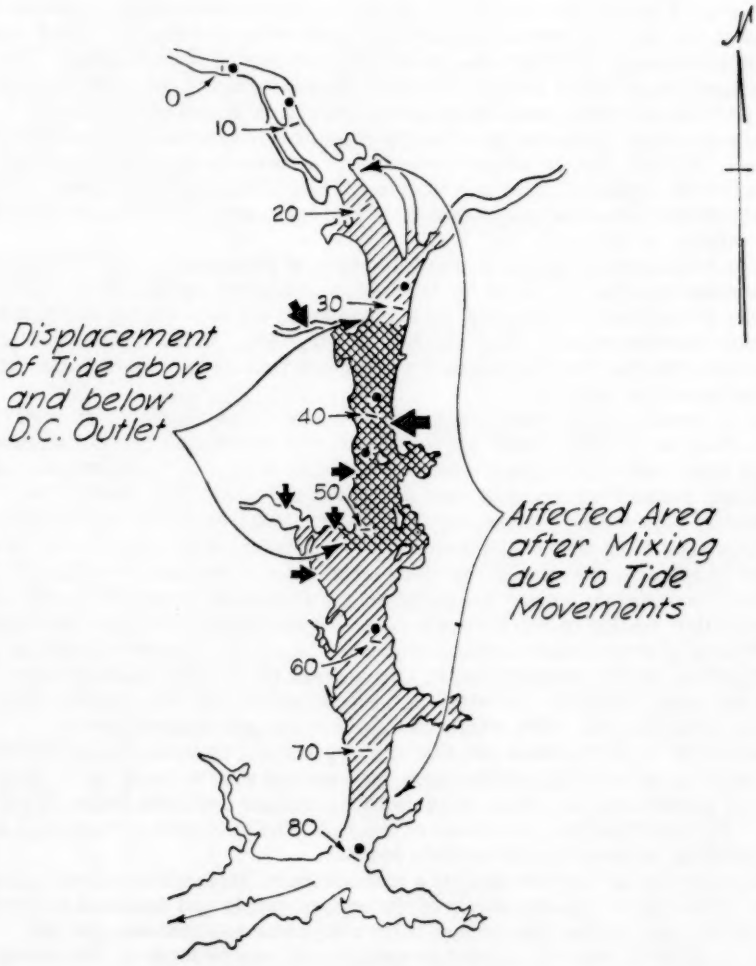
FIG. 3



POTOMAC RIVER AT WASHINGTON

EXTENT OF TIDAL DISPLACEMENT

FIG. 4



POTOMAC RIVER AT WASHINGTON

EFFECT OF TIDES ON DISPERSAL OF POLLUTION

10 5 0 10 20 30

SCALE IN 1,000 FEET

the Delaware River for the Pennsylvania Water Resources Commission by a Board of Engineers.[1]

Figure 5 shows the results of calculations using conventional methods applied on the basis of natural stream flow unaffected by tides, for B.O.D. and Dissolved Oxygen in the stream, compared with actual observations. The calculated lines shown are the result of determination of constants for various portions of the stream, based on the survey data, and utilize those constants which appear to give results most nearly approaching the observed values. At best, the calculated lines depart materially from the observed pattern. The effect of tidal movements in transporting pollution loads over considerable distances upstream and downstream and in ironing out the peaks and valleys, is apparent.

The relation between the dissolved oxygen at Philadelphia and the rate of natural stream flow is shown on Figure 6, for each of six sampling points and for the average of the sampling points, for river surveys during warm water periods between August, 1949, and September, 1951. Below about 8,000 cfs, it is apparent that the magnitude of the stream flow had no appreciable effect on the dissolved oxygen.

In recognition of the fundamental differences in the characteristics of the tidal river as compared with the continuous one directional flowing stream to which usual methods of oxygen balance calculations apply, a second so-called "rational method" of approach was developed and used. This method is primarily applicable to lakes, bays, ponds or estuaries having considerable surface area for aeration and numerous and substantial mixing forces. It is based on the principle that if the mean oxygen deficiency and the total B.O.D. load are both known for any set of inflow and temperature conditions, then the permissible loading to maintain any other oxygen deficiency under the same conditions of temperature and inflow can be calculated by direct proportion. Calculations by this method, taking into account the B.O.D. loads of the inflow and sludge deposits, resulted in the conclusions that whereas the prevailing loads in 1949 and 1950, which included sewage and waste loads of approximately 735,000 pounds per day of 5 day B.O.D., caused oxygen depletions approaching or reaching 100 per cent, sewage and wastes loads up to about 340,000 pounds per day could be assimilated without depletion below 50 per cent. For depletion to a minimum of 3 p.p.m., the allowable sewage load was computed to be about 450,000 pounds per day.

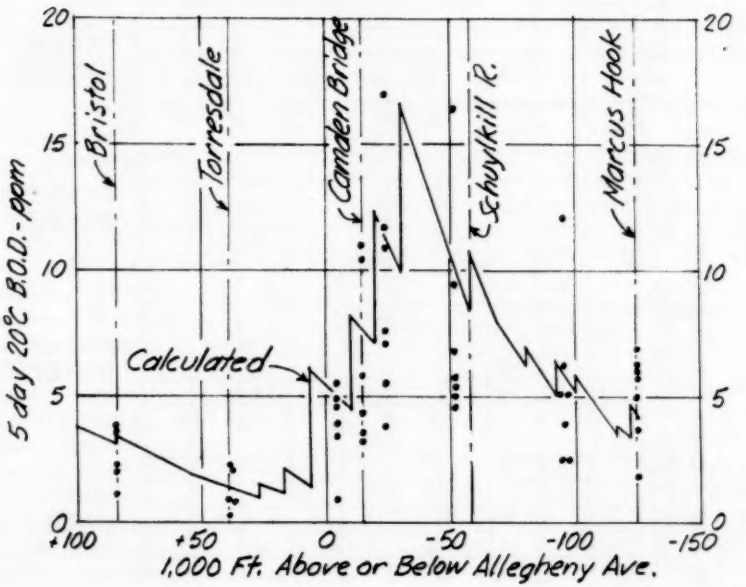
Recently the writer has applied a much simpler streamlined check calculation in which all considerations of the oxygen supply and demands of the incoming stream and the demands of bottom deposits are ignored, and the capacity of the stream to assimilate sewage and wastes loads is calculated by direct proportion to the oxygen depletion. The results of this extremely simplified method check those of the more involved method so closely that the required removals by treatment works as determined by the two methods would differ by not over one or two percentage points.

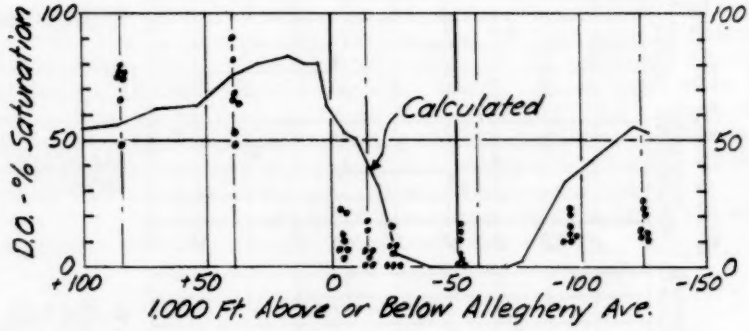
Potomac River at Washington

Since 1937, a period of nearly 20 years, the Department of Sanitary Engineering of the District of Columbia has maintained an active program of sampling and analysis of the waters of the Potomac River at Washington, at

1. Board of Engineers: Gannett, Fleming, Corddry & Carpenter, Inc.; The Chester Engineers; Greeley and Hansen.

FIG. 5



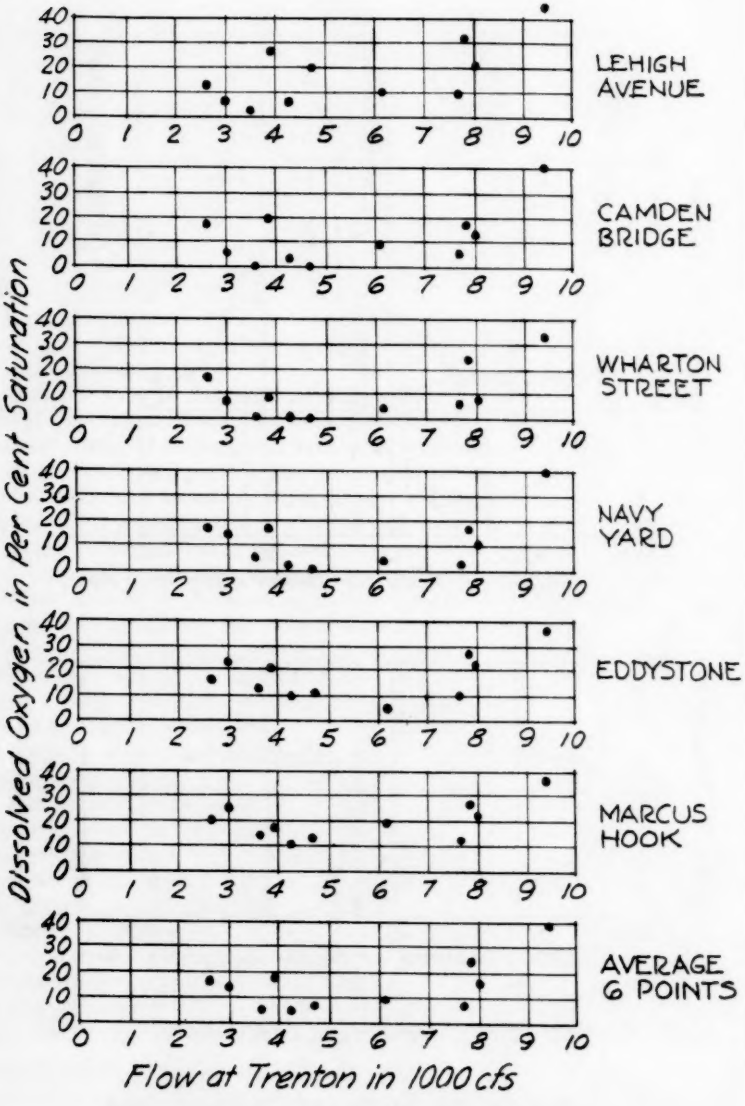


Note: Plotted Points are Field Observations

DELAWARE RIVER AT PHILADELPHIA

B.O.D. AND DISSOLVED OXYGEN

FIG. 6



DELAWARE RIVER AT PHILADELPHIA
DISSOLVED OXYGEN AT VARIOUS STREAM FLOWS

seven points from the Three Sisters islands near the head of tidewater to Fort Washington, covering a total length of river of about 80,000 feet or about 15 miles. The locations of the sampling points and of the principal sewer outlets are shown on Figure 7. Nearly all of the metropolitan area sewage is discharged to the river midway in the reach covered by the surveys. The survey runs have generally been made at weekly intervals during the summer months and less frequently during the winter.

Figure 8 shows a few selected dissolved oxygen profiles as determined by individual survey runs, for stream flows of approximately 1,500 cfs in the upper group and approximately 4,500 cfs in the lower group. The principal difference is that the sag occurs further upstream for the lower stream flows.

Figure 9 shows the mean and the minimum dissolved oxygen values for all runs within the 26° to 31° temperature range for the period from 1943 through 1955. The upper profiles are for all runs when the stream flow was less than 5,000 cfs, and the lower profiles for stream flows over 5,000 cfs. In both flow ranges, the minimum values are substantially below the mean values, and the effect of transfer of the pollution a considerable distance upstream from the point of entry, due to tidal movements, is apparent.

Figure 10 shows the minimum dissolved oxygen encountered at any point for all of the survey runs in the 21° - 31° temperature range. The upper diagram is for the years 1937 through 1942, when the average sewage load was approximately 125,000 pounds per day of 5 day 20° B.O.D. The lower diagram is for the years 1943 through 1955, when the average load was about 187,000 pounds per day. With the ratio of the later to the earlier sewage loads of 1.50, the ratio of oxygen depletions was 1.44 for the lowest and 1.52 for the mean of the minimum determinations. Thus, the greatest depletions of dissolved oxygen below saturation have been approximately in proportion to the sewage loads.

Based on the studies of the river surveys, it has been concluded that under present conditions as regards bottom deposits the Potomac River at Washington can assimilate sewage pollution amounting to 110,000 pounds per day of 5 day 20° B.O.D., and that with the reduction in bottom deposits expected to accompany future higher degrees of treatment, the assimilation capacity will be somewhat higher, in the neighborhood of 120,000 pounds per day, without depletion of dissolved oxygen at any time or at any point below 3 p.p.m., and only on rare occasions below 4 p.p.m. Also, the evidence of the survey records is that very little benefit would result from augmentation of the minimum stream flow within the range of reasonable possibility.

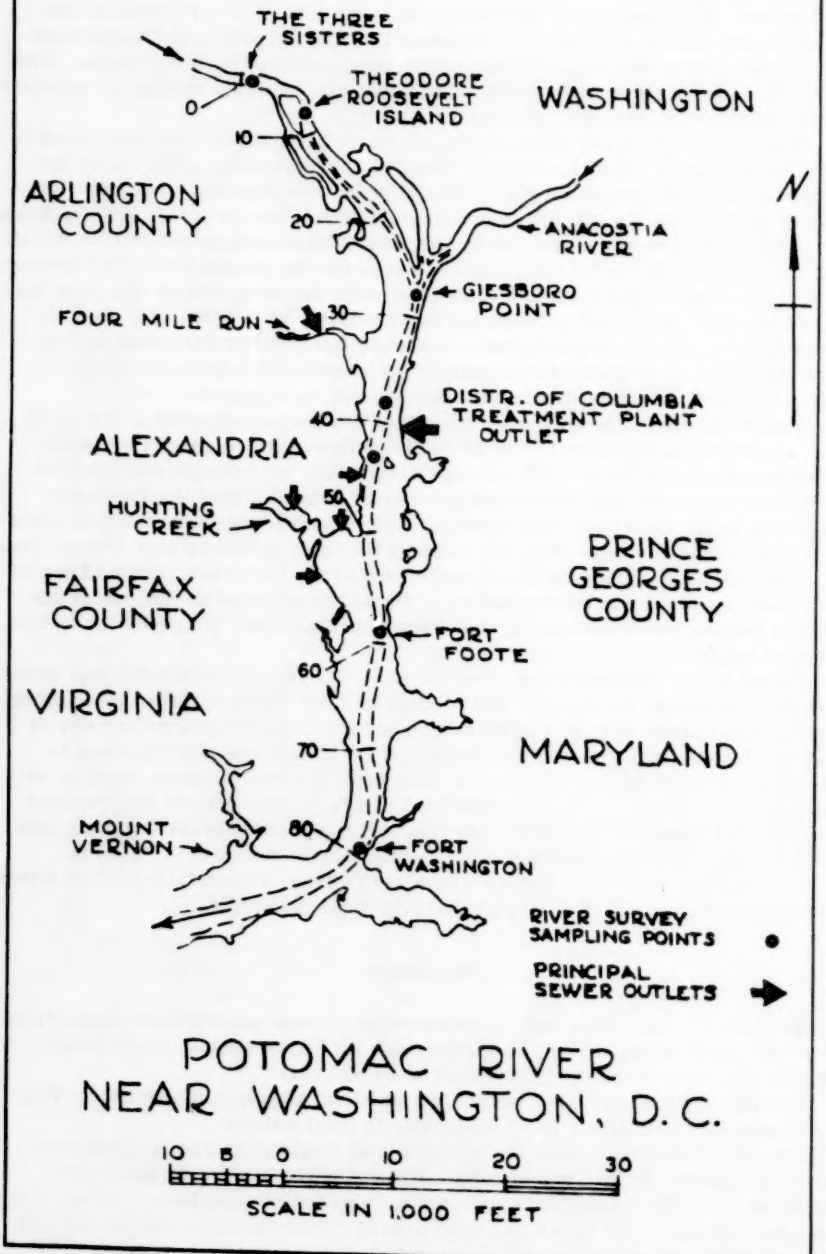
Discussion

Methods of calculating oxygen balances or stream assimilation capacities, if sound, must stand the test of agreement with known results under known conditions. Otherwise, they obviously are incorrect.

The calculation methods customarily used for streams unaffected by tidal movements do not appear to be applicable to tidal waters.

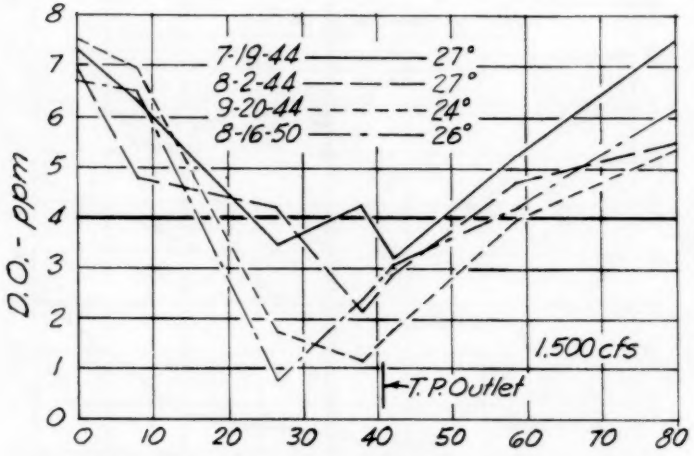
Results of studies at both Philadelphia and Washington are in agreement as to the effects of tidal movements. Where the tidal action is more pronounced, as at Philadelphia, the stream survey results are less erratic. This may well be due to the more thorough mixing in the course of the initial tide cycles.

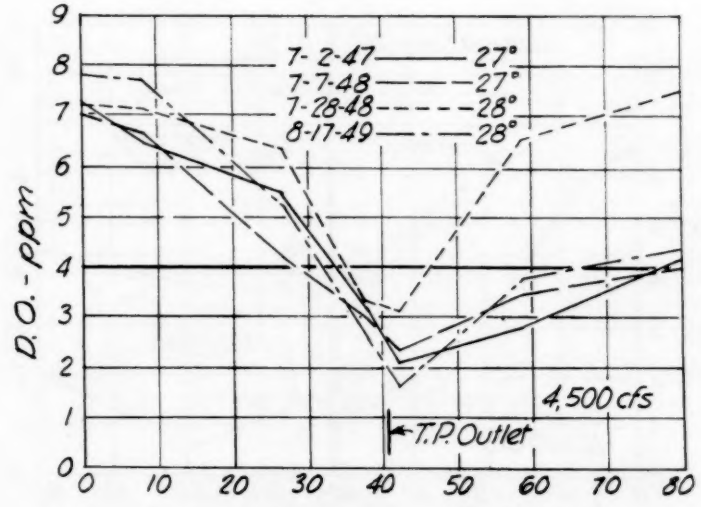
FIG. 7



POTOMAC RIVER NEAR WASHINGTON, D. C.

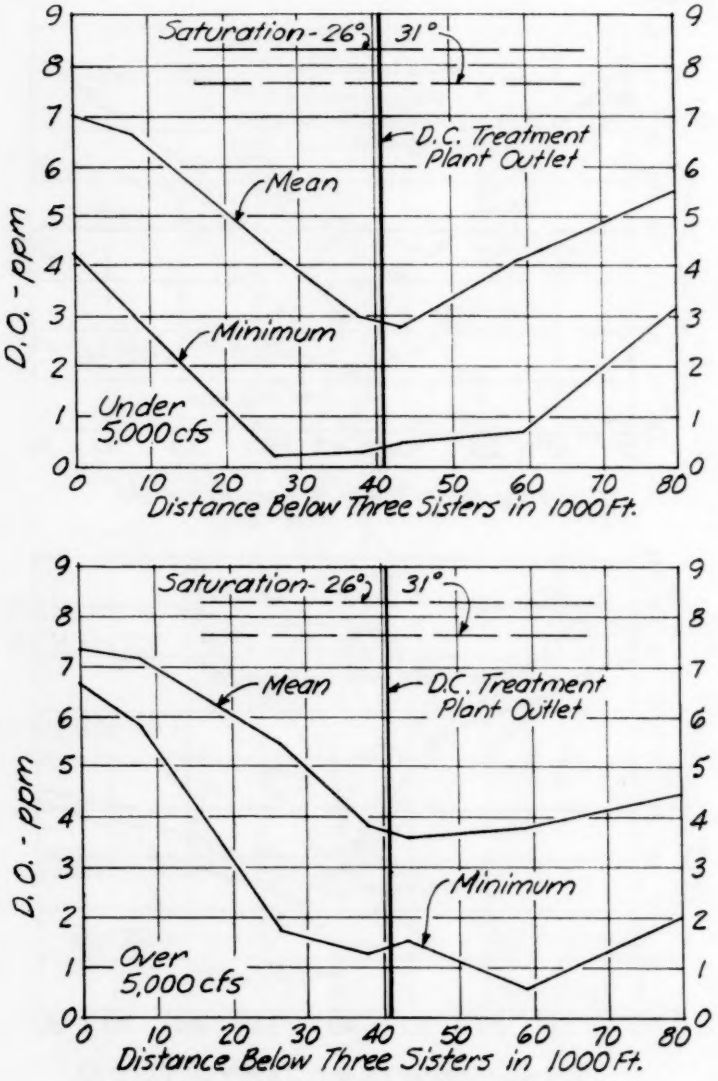
FIG. 8





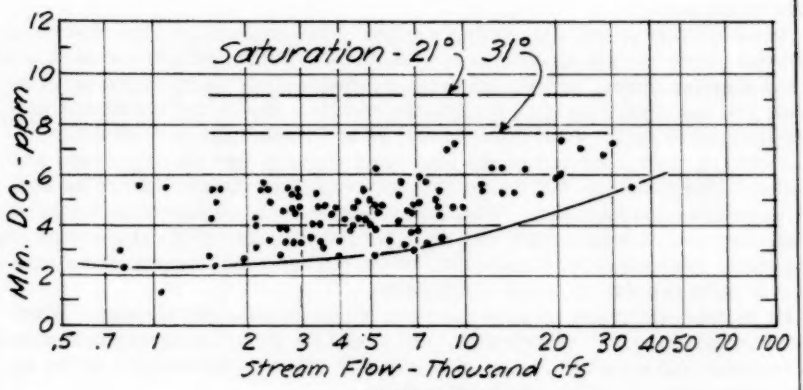
POTOMAC RIVER AT WASHINGTON
DISSOLVED OXYGEN PROFILES

FIG. 9



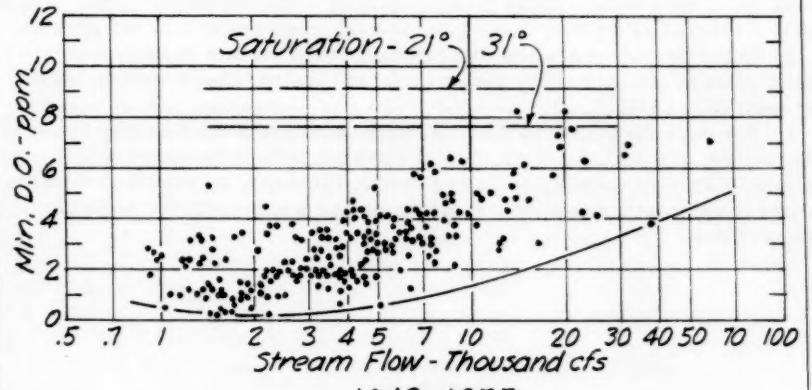
POTOMAC RIVER AT WASHINGTON
DISSOLVED OXYGEN - VARIOUS LOCATIONS
ALL SURVEYS, 1943-1955, 26°-31°C.

FIG. 10



1937-1942

Estimated Aver. Sewage Load
125,000 Lb./Day 5d. 20°B.O.D.



1943-1955

Estimated Aver. Sewage Load
187,000 Lb./Day 5d. 20°B.O.D.

POTOMAC RIVER AT WASHINGTON
MINIMUM DISSOLVED OXYGEN
ALL SURVEYS, 21°-31°C.

The importance of extensive river surveys cannot be over-emphasized, regardless of the type of stream. Sewage treatment plant operators should at most places obtain river survey data to a much greater extent than they have in the past.

The objective of any calculation method is the extension of the results of surveys under certain conditions to calculated results under other conditions. In the simpler cases, calculation methods customarily used, based on relatively few surveys, may give acceptable results. Where the conditions are complicated by major tidal movements, as at Philadelphia and Washington, it is evident from a review of the long-time records that many surveys are needed to establish the full range of river conditions under adverse as well as favorable circumstances. Where surveys cover a considerable range of conditions over a long period, the need for and usefulness of calculations may be greatly reduced if not eliminated, as the survey results themselves may clearly point the way to sound conclusions.

No method of oxygen balance calculation can be considered exact. Whatever the approach, the interpretation of available pollution survey data should be realistic and directed toward a reasonably close determination of the assimilation capacity of the receiving waters.

Conclusions

1. Tidal streams such as the Delaware at Philadelphia and the Potomac at Washington have substantially greater capacity to assimilate pollution at low river discharges than they would have if tidal movements were not present.
2. In the two cases studied, the capacity of the stream to assimilate pollution loads is approximately proportional to the depletion of oxygen below the saturation level.
3. For both the Delaware River at Philadelphia and the Potomac River at Washington, and perhaps in other tidal streams, within the range of low stream flows obtainable by river regulation, little may be gained as regards pollution assimilation capacity by increasing or augmenting the minimum natural flows.

Paper 1409 October, 1957 SA 5

Journal of the
SANITARY ENGINEERING DIVISION
Proceedings of the American Society of Civil Engineers

ANAEROBIC REDUCTION OF MANGANESE IN RESERVOIRS

John H. Wiedeman[1] and Robert H. Fetner[2]
(Proc. Paper 1409)

ABSTRACT

Manganese may appear seasonally in some impoundments while part of the impoundment is anaerobic. One possible source of this manganese may be the reduction of insoluble manganese dioxide found in the soil by the carbon dioxide produced as an anaerobic by-product of biological metabolism.

INTRODUCTION

The problem of manganese in water has become increasingly important to the waterworks industry as a by-product of many of the large flood control and power developments. Manganese may appear in the lower layers of reservoirs during the period of the year that an anaerobic condition exists and water used for power is commonly drawn from these layers and released into the river. Such water is objectionable to the consumer because the soluble manganese will form a dark brown precipitate when oxidized. This precipitate stains plumbing and laundry, causes colored water, and interferes with industrial processes. Water plant removal of manganese is possible, but difficult, expensive, and often uncertain.

The exact mechanism of solution of manganese in the hypolimnion of lakes is unknown. It has been suggested that manganese may act as a terminal hydrogen acceptor of anaerobic bacterial respiration (1,2,3) or that solubization of manganese may be a result of biologically-induced changes in oxidation-reduction potential,(4) pH,(5,6,7,8) or the chemical activity of such metabolic by-products as carbon dioxide.(9,10)

The objective of the present study was to determine if manganese could be

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2. Asst. Research Prof., Eng. Experiment Station, Georgia Inst. of Technology, Atlanta, Ga.

reduced by sludge gas, independent of the sludge itself. Sludge produces gases similar in composition to those evolved from decaying organic matter in lake beds and these experiments were designed to determine whether or not such gases were a possible cause of manganese solubization. Since other experimenters believe the reduction of manganese to be part of biological systems, this variable was eliminated by isolating the sludge from the manganese.

Materials and Methods

The apparatus used for an individual sample is diagrammed in Figure 1. A 2-liter bottle, (a), containing a mixture of digested sewage sludge and proteose peptone was used as a gas source. Controls used compressed carbon dioxide, nitrogen, and air. The gas was passed via connecting tubing, through a diffuser, (b), into the sample of an aqueous suspension of insoluble manganese dioxide, (c). The excess gas went into a calibrated one-liter collection tube, (d).

Before each run the collection tube was filled with water, the water remaining in the tube until it was displaced by gas. The diffuser assembly and sample container were of glass with ground glass connections so that the diffuser assembly could be removed for cleaning or sampling. The gas diffuser was of fritted glass.

Daily measurements were made of the manganese content of a sample of water through which gas had been passed. The quantity of gas and the pH of the sample were measured as supplementary data. Soluble manganese was determined by the persulphate method.(11)

The daily test procedure consisted of removing the water sample, dividing it into two 50-ml portions and then analyzing one for pH and the other for manganese content. The one to be analyzed for manganese was filtered through Whatman #4 filter paper. The sample vessel containing manganese dioxide was replaced in the apparatus after 100 ml of boiled tap water was added. The tap water had been boiled for 10 minutes and sealed after cooling. The final step in the procedure was to measure the gas and refill the collection tube.

Results

Five runs were made in these experimentations. Each consisted of a series of individual experiments using the same materials.

Sludge Gas

Sludge gas was bubbled through the water-manganese sample for about 24 hours before tests were run. The daily amount of gas bubbled through the sample varied (see Table I); the maximum amount was 550 ml per day for the 10 days of the runs. The third day's test had more manganese than either the fifth or eighth day's tests with pH and gas production bracketed between the two days.

The variations may be an expression of the daily change in sludge gas composition. If one of the components of sludge gas reduces manganese dioxide then a variation in gas composition might result in a variation in manganese concentration. The same is true for pH.

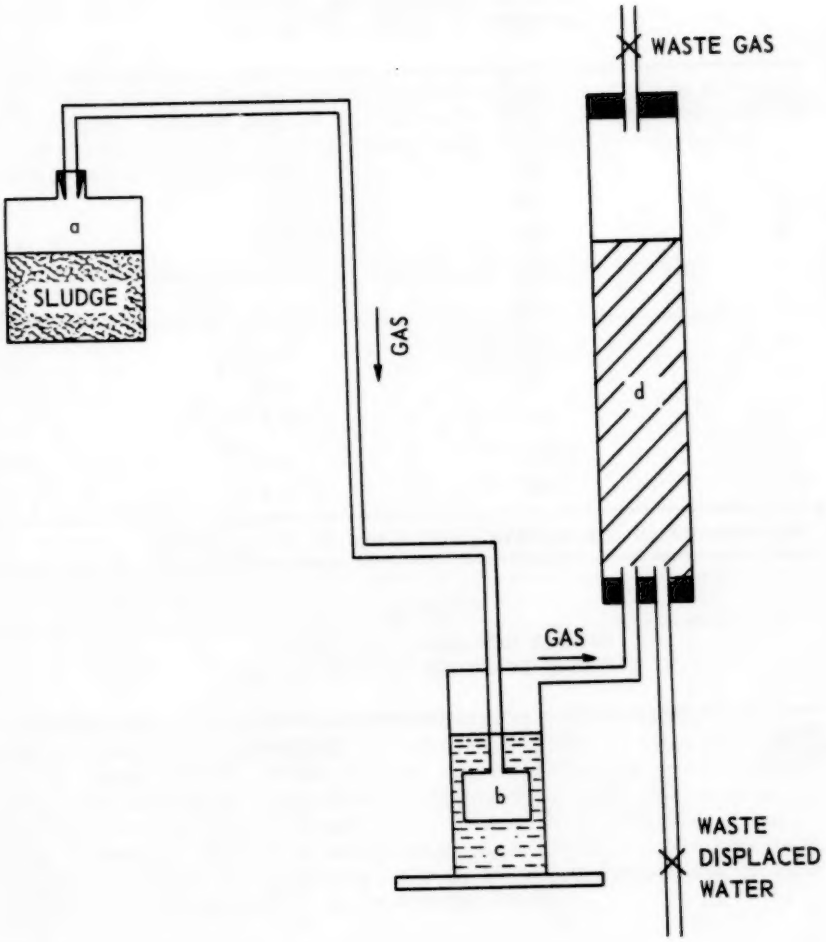

Figure 1. Diagram of Apparatus.

TABLE I

SOLUBLE MANGANESE, pH, AND GAS
PRODUCED BY SLUDGE GAS PER DAY

Time (days)	Gas† (ml)	Manganese (ppm)	pH
1	300	0.0	5.2
2	420	0.5	-
3	320	0.6	5.5
4	220	0.4	-
5	400	0.3	6.2
6	550	0.5	-
7	80	0.2	5.3
8	370	0.3	5.3
9	150	0.3	5.6
10	300	0.3	-

†Gas measured at approximately 22° C and 76 cm of mercury

TABLE II

SOLUBLE MANGANESE, pH, AND GAS
PRODUCED BY CARBON DIOXIDE PER DAY

Time (days)	Gas† (ml)	Manganese (ppm)	pH
1	180	0.5	5.4
2	850	0.5	5.2
3	740	0.8	4.6
4	980	0.3	5.1
5	900	0.5	3.6††

†Gas measured at approximately 22° C and 76 cm of mercury

††pH of the sample was adjusted to 3.9 before the run began

Carbon Dioxide

The data of Table II indicate that reduction of manganese dioxide may be caused by carbon dioxide, one of the principal constituents of sludge gas. The result of using carbon dioxide instead of sludge gas gave about the same quantity of soluble manganese as did sludge.

Nitrogen

The results given in Table III show that nitrogen had no effect on manganese dioxide. There was no manganese reduction in any of the samples, even though the pH was artificially lowered with sulphuric acid on the last day (expressly to study pH effects).

TABLE III

SOLUBLE MANGANESE, pH, AND GAS PRODUCED BY NITROGEN PER DAY

Time (days)	Gas (ml)	Manganese (ppm)	pH
1	950	0.0	6.5
2	850	0.0	6.8
3	620	0.0	7.0
4	830	0.0	7.2
5	1000	0.0	5.6†

†pH of the sample was adjusted to 3.9 before run

Air

Table IV gives the results of a control designed to determine the importance of oxygen in the manganese cycle by using air. Air contains about 78 per cent nitrogen and 21 per cent oxygen. The only other gas in air of importance to this problem is carbon dioxide. The carbon dioxide content of air is about 0.03 per cent. Carbon dioxide will contribute to the reduction of manganese as shown in Table II. It would seem, therefore, that oxygen inhibits the formation of divalent manganese. The pH of the manganese-water sample was lowered to 6.0 and still no manganese was reduced.

Manganese Concentration

Table V gives the results of an experiment designed to study variation of contact time between manganese dioxide and sludge gas. The tests were taken at intervals of 5, 10 and 14 days. The increase of the amount of manganese as a function of time with the final values of 1.0 ppm for 10 and 14 days would seem to indicate a chemical reaction in which an equilibrium condition is reached in from 10 to 14 days. Figure 2 shows the one-day averages plotted with the 5-, 10- and 14-day values of manganese concentration. The curve of Figure 2 is similar to the curve of a first-order reaction.

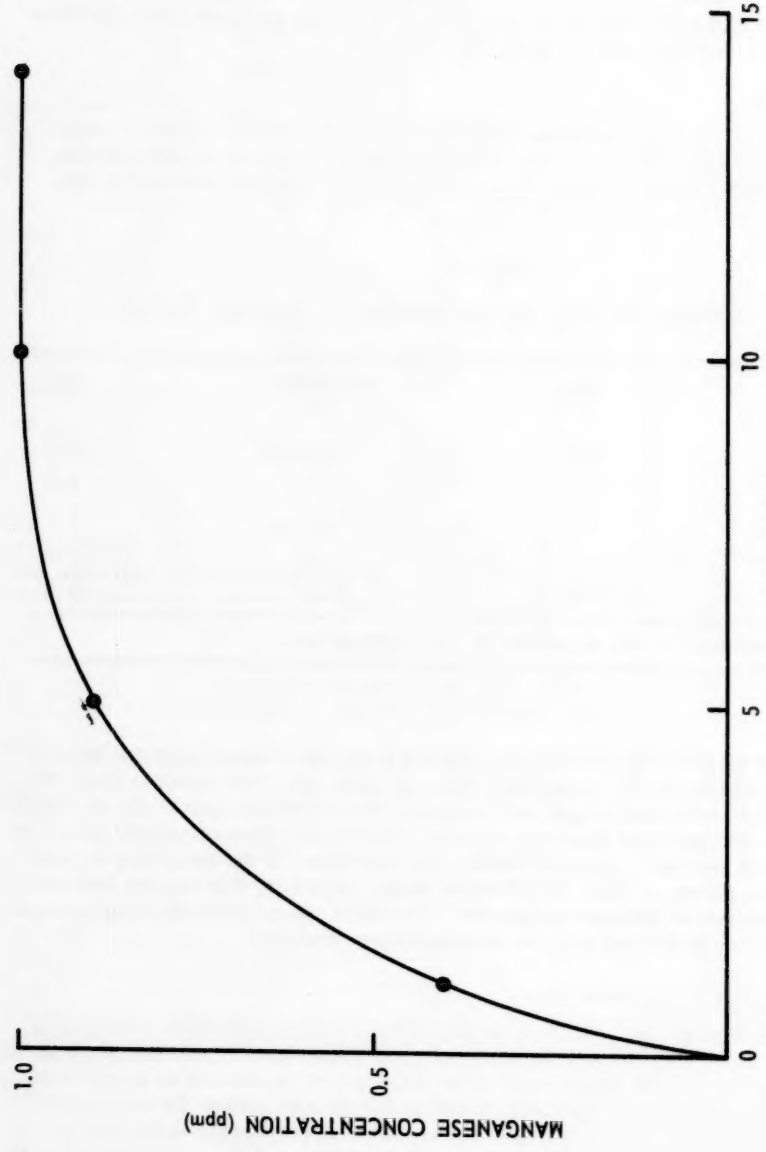

Figure 2. Concentration of Manganese Produced by Sludge Gas as a Function of Contact Time.

TABLE IV

SOLUBLE MANGANESE, pH, AND GAS PRODUCED BY AIR

Time (days)	Gas (ml)	Manganese (ppm)	pH
1	425	0.0	6.8
2	720	0.0	6.8
3	620	0.0	6.9
4	980	0.0	6.9
5	840	0.0	6.0†

†pH of the sample was adjusted to 3.9 before run

DISCUSSION

The results indicate, under the conditions of these experiments, that manganese dioxide may be reduced as a result of carbon dioxide being bubbled through water in contact with reagent grade manganese dioxide. Using the same flow-rate, sludge gas diffusion through the sample produces a manganous-manganic equilibrium within 10 to 14 days. Carbon dioxide

TABLE V

TOTAL SOLUBLE MANGANESE, pH, AND GAS PRODUCED BY SLUDGE GAS

Time (days)	Total Gas (ml)	Total Manganese (ppm)	pH
1	300	0.4	5.5
5	900	0.9	5.5
10	2400	1.0	5.2
14	5050	1.0	4.6

appears to be the causative agent in the reduction of manganese dioxide by sludge gas because sludge gas and carbon dioxide produce almost the same amount of manganese under identical conditions, and carbon dioxide is one of the principal constituents of sludge gas. The hydrogen ion concentration within the range of this experiment seemed to have no effect.

It is difficult to relate these data to lake conditions. The conditions on a lake bottom do not match the conditions of this experiment in many respects. Rate of gas diffusion and concentration of the reactants are greater in the laboratory experiments. The time allowed for reaction, pH and pressure are less in the laboratory. Whether a change in the conditions of the experiment would change the quantity of manganese reduced is unknown; however, the results

seem to indicate there would be some reduction of manganese under reservoir conditions.

The purpose of this study was not to determine the mechanics of the manganese dioxide-carbon dioxide reaction, but rather to show that such reaction exists. To relate the reaction in the laboratory as closely as was possible to the reaction that occurs in lake bottoms, impure manganese and water were used.

ACKNOWLEDGMENT

This work was supported in part by Grant Number RG4363(C) of the National Institutes of Health.

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Paper 1410 October, 1957 SA 5

Journal of the
SANITARY ENGINEERING DIVISION
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NIAGARA RIVER POLLUTION*

Raymond W. Hess[1]
(Proc. Paper 1410)

SYNOPSIS

The tremendous industrial development along the Niagara River created a pollution problem that has increased with the passage of time. Considerable study has been made into the pollutional problem and its solution. Progress is definitely being made to keep pollution to a minimum.

On July 19, 1928, before the Sanitary Engineering Division of the ASCE, at a meeting of the Society in Buffalo, New York, Earl Devendorf of the New York State Department of Health presented a paper on the pollution problem of the Niagara River. Obviously, there was a pollution problem then, long before that, has continued to be since that time, and will continue to be a potential problem, at least, as long as the population increases and industry expands on the Niagara Frontier.

Although the author prefers to discuss that part of the problem with which he has had direct experience, beginning in the late 1930's, which seems to be the beginning of actual pollution abatement in the Niagara River on a significant scale, he feels that he should outline briefly the developments leading up to that time as garnered from publications and contacts with those who have had direct experience.

First, let us take a brief look at some of the basic aspects of the Niagara River and its adjoining lands. The Niagara River, flowing north from Lake Erie to Lake Ontario, is 37 miles in length and has an unusually uniform flow

Note: Discussion open until March 1, 1958. Paper 1410 is part of the copyrighted Journal of the Sanitary Engineering Division of the American Society of Civil Engineers, Vol. 83, No. SA 5, October, 1957.

*Presented at a meeting of the American Society of Civil Engineers in Buffalo, N. Y., June, 1957.

1. Coordinator, Pollution Research & Control, National Aniline Div., Allied Chem. & Dye Corp., Buffalo, N. Y.

averaging about 200,000 c.f.s. Its level drops 326 feet between the two lakes. About one-half of this is at Niagara Falls, something over half way to Lake Ontario. It is divided into two main channels by Grand Island for about half the distance between Lake Erie and the Falls.

The exceptionally uniform flow and sharp drop has encouraged development of low cost electric power. This, together with a bountiful supply of water and the economies of Great Lakes transportation, has attracted many industries including chemical, electrochemical, electrothermal, steel, fertilizer, pulp and paper, and petroleum refining.

The area adjacent to these waters has a population of over 1,000,000 people, about 80% concentrated in Buffalo, Tonawanda, North Tonawanda and Niagara Falls, New York and Niagara Falls, Ontario.

Until the Buffalo treatment plant was completed in 1938, but few installations were made to treat the continually increasing amounts of sewage and industrial wastes flowing into the Niagara River directly and through its tributaries.

In its brochure of 1939, announcing the dedication of the Buffalo Sewage Treatment Plant, the Buffalo Sewer Authority (B.S.A.) stated "For fifty years or more.....health authorities on both sides of the boundary had been observing with growing apprehension the steady deterioration of their water supply and the increasing incidence of typhoid and kindred ailments". That takes this apprehension back to 1890 or earlier.

The first report of an actual quality survey of Niagara River water, which has come to attention, is that of the New York State Department of Health in 1907 to determine the suitability of its use as a source of water supply for the city of Niagara Falls, New York. The conclusion was that sewage from the city of Buffalo was a menace to that use.

Another survey in 1913 by that agency concluded that water supplies of the Tonawandas and Lockport, which are taken from the Niagara River, were polluted by sewage.

During the same year, a comprehensive survey was conducted by the International Joint Commission (I. J. C.) which was formed when, quoting again from the B. S. A. dedication brochure "The Canadian protests came to a head in 1909 when a treaty between the United States and Canada was signed, expressly providing that the waters herein defined as boundary waters and waters flowing across the boundary shall not be polluted on either side to the injury of health or property on the other. The Niagara River was particularly named as among the most important of these boundary waters."

A progress report in 1914 delineated the extent of sewage pollution. In 1916 remedial measures were recommended, but action on these was delayed first by World War I and, then by just what else is concealed in such generalizations as "the problems of reconstruction which followed" until 1935, when the "State Department of Health summarily mandated the city of Buffalo to discontinue forthwith the menacing nuisance of pollution of the River waters".

However, in the meantime, concern about this situation was not entirely dormant as was indicated by reference at the beginning of this paper by Earl Devendorf in 1928. For the first time, in reports noted, Mr. Devendorf referred to certain industrial plants as sources of pollution.

During 1928, the New York State Department of Conservation completed a biological survey of these waters. Sources of pollution by both sewage and industrial wastes.were listed in the report on this survey.

Surveys made in 1929, 1931 and 1933 by the New York State Department of Health indicated that pollution of the Niagara River had become progressively worse since its first survey in 1907.

Another indication that concern about the problem was not entirely forgotten is a paper titled "The Problem of Interception and Treatment of Sewage at Buffalo, New York" which was given by C. L. Howell, Assistant City Engineer, at a meeting of the New York State Sewage Works Association in 1929.

The mandate to the Buffalo Sewer Authority to abate pollution from sources in the city of Buffalo seemed to include abatement of pollution by industrial wastes within the city's confines. A survey in 1936 under the direction of Dr. George E. Symons, Chief Chemist, Buffalo Sewer Authority, disclosed that one of the sources of industrial wastes of most concern was the Buffalo River, the mouth of which is at the source of the Niagara River in Lake Erie. The sources of most of these wastes were two chemical plants, a refinery, a steel plant and a coke plant, located 4.5 miles from the River's mouth. It was obvious that most of these wastes could not be diverted to the Authority's sewerage system because of possible damage to structures or treatment processes, because treatment in this primary plant would be inadequate, or because of hazards to the public.

Accordingly, representatives of these five companies met with representatives of the Sewer Authority, the city and state government to discuss the problem and make plans for solving it. The program evolved was one of investigation and treatment by each company individually before discharge into the Buffalo River. It was comprised of an over-all reduction of waste load with particular emphasis on B. O. D. reduction.

While these plans were being developed, during the Fall of 1937, great numbers of dead fish were seen floating into and along the shores of the Niagara River. Although this occurrence was attributed largely to industrial wastes from the Buffalo River, there were some differences of opinion among governmental agencies and other observers. Some thought that it might have been caused by concentration of untreated city sewage at one point in the Niagara River by a large intercepter which had just been completed to replace the many scattered outlets in the Niagara and Buffalo Rivers. It does not seem to have occurred to anybody that it might have been due largely to natural causes as was indicated to be the case, by an extensive investigation, for a similar phenomenon in 1954. Nevertheless, this incident gave impetus to the program of research, surveys and their application to waste treatment for the next 4-5 years.

During the following 4-5 years, the amount of wastes was increased by heavier production. Investigations and waste treatment were subordinated but not eliminated by the urgent demands of World War II.

After the cessation of hostilities, in 1946, the Buffalo Sewer Authority under the direction of Dr. George E. Symons, then its consultant, made another survey of the Buffalo River and the wastes from its industries, with the cooperation of industry which supplied installations for measurements of flows and sampling, and some of the personnel. As the result of this survey, Dr. Symons recommended a 50% reduction of the waste load, with particular emphasis again on B. O. D. reduction to restore an oxygen balance in the stream, and installations to bring water from Lake Erie, through the plants' cooling systems, into the Buffalo River for purpose of pollution abatement.

The basis of this proposal was increased flow, dilution, a supply of dissolved oxygen and natural alkalinity to aid purification and, especially, to reduce the magnitude of slugs which were occasionally swept out into the Lake and thence into Niagara River by seiches, reversal of winds and heavy run-off. During the Summer, when stream flows are very low in the six mile dredged basin of 165,000,000 cu. ft. which is known as the Buffalo River, retention period of the wastes may be for several weeks.

A series of conferences with representatives of the Sewer Authority, the State Health Department and the State Conservation Department was held. Dr. Symons' recommendations were agreed to, as objectives, by all concerned and industry's activities proceeded accordingly until 1955 when they were somewhat modified by the program of the New York State Water Pollution Control Board which had been established in the meantime by a new law. In 1954, Nussbaumer, Clark and Velzy Inc., at industry's expense, made an engineering survey which indicated the cost of the Lake water project to be about $5,300,000. Many conferences between industries and between industries and governmental agencies were held on the project, which had been titled the Buffalo River Pollution Abatement Project-Water System, but was not consummated during this period because of a number of technical, financial and legal difficulties, and a sponsorship problem not then resolved. A clarifying report on that alone could take more time than allowed for this paper.

In the meantime, there had been another development on the program for the entire Niagara River Basin. In 1948, the I. J. C. issued its "Objectives for Boundary Waters Quality Control". During the following year it made a survey of the quality of water in the Niagara River and its tributaries, and of the quality of effluent from all sources. The survey showed that these "Objectives" were not being met in all respects, particularly as to phenol limits of 2 ppb average and 5 ppb maximum, and as to the median coliform M.P.N. of 2400 per 100 ml, in the Niagara River, after "initial dilution".

On November 15, 16 and 17 and on December 13, 14 and 15, 1949, the I. J. C. held public hearings to develop additional information. Representatives of municipalities and industries which were contributing sewage and wastes to the Niagara River were asked as to their opinions of the Commission's "Objectives" and what they had done and planned to do about their wastes. Representatives of public water supplies, public health, conservation, sportsmen and the public generally presented their views on the problem. Copies of a 744 page transcript of these hearings were made available to the public.

The "Objectives", data on the survey, and recommendations were published in 1951 in a 312 page report titled "Report of the International Joint Commission, United States and Canada, on the Pollution of Boundary Waters". Corrective measures recommended include the Buffalo River Pollution Abatement Project - Water System, in addition to extensive treatment of sewage and industrial wastes for the entire area, to improve the quality of water in the Niagara River.

At this point, it might be well to observe that the I. J. C. itself has no authority to enforce pollution abatement programs. Its responsibility and authority is limited to making recommendations to State, Provincial and National governments of the United States and Canada for abatement of pollution in boundary waters. However, this authority has high prestige,

especially since it may include recommendation of legal action by the U. S. and Canadian governments under the highest law of the land, an international treaty.

Up to this time, the New York State pollution control programs for the Niagara Frontier, as was the case for all other areas of the State, were administered separately but cooperatively by the State Health Department, the State Conservation Department, the Erie County Department of Health, the Buffalo Sewer Authority and, for oil pollution of navigable waters, the U. S. Army Engineers. The Health Departments had blanket authority to protect water supplies in relation to public health, but had only little to guide them in the way of criteria in this connection. The Conservation Department had no authority to protect fish life other than to prosecute after proving responsibility for fish mortality.

All this was changed in 1955 by application to the area of Chapter 666 of the New York State Public Health Law, now Article 12 of the Public Health Law, which was enacted in 1949. This law created a State Water Pollution Control Board to administer all aspects of water pollution control. It requires that all waters of the State be classified according to their "best usages", in other words, their most appropriate usages—such as drinking, fish propogation, bathing, agriculture, industrial, waste disposal, etc. - in each locality, taking into consideration all factors involved. Each class has chemical, physical and biological standards of quality for uses specified. That system is covered by "Rules and Classifications and Standards of Quality and Purity for Waters of New York State" which was issued by the Water Pollution Control Board in 1950. The law, before enactment, and the Classification Standards System, before adoption, had the best thought of all interests of the people affected, both in conferences and at public hearings.

Leading up to this new approach, an extensive survey, in which the data in previous surveys as well as new data developed were given consideration, of waters on the New York side of the Niagara drainage basin was made as required by the law. The findings of this survey and recommended classifications are covered by a report of some 130 pages titled "Lake Erie - Niagara River Drainage Basin Series, Report No. 3" which was widely distributed early in 1953.

Following public hearings on April 21, 1953 and on June 30, 1954, the classifications were issued on December 6, 1954. As the result of these hearings, some alterations of classifications from the original proposal were made. The most important of these were for the Buffalo River and the Niagara River. Class E, instead of the originally proposed Class D, was adopted for the Buffalo River by the Water Pollution Control Board in recognition of the valid position taken by Industry that conditions requisite for fish survival were no longer, and had not for many years been, a 'best usage' of these waters in the heart of industrial Buffalo, and that Class E would not adversely affect quality standards in view for waters into which the River flows.

Class A Special, instead of the originally proposed Class C Special was adopted for the main segment of the U. S. side of the Niagara River on the basis of strong public opposition to the latter, which would not include bathing and new public water supplies as "best usage". Class A Special encompasses the "Objectives" of the I. J. C., but requires approval of local health officials for bathing and special treatment for use as public water supplies until the I. J. C. "Objectives" are met. However, the quality

standards of this class will be very difficult to meet as long as practically all the sewage systems on New York's Niagara Frontier are for both sewage and storm water with many by-passes away from the treatment plant when the run-off is heavy. During these periods, most of the untreated sewage from nearly a million people may be carried by the U. S. segment of the river.

Although there had been public agitation about dead fish in the Niagara River from time to time since 1937, it reached a climax in March 1953 and, especially, March 1954, after much had been done to abate pollution, and while this control program of the New York Water Pollution Control Board was being developed. Local newspapers gave many columns to crusading self-appointed experts who attributed the cause to industrial wastes. Industry ignored the tirade until a hearing was called in Washington on April 12, 1954 on H. R. 5431, H. R. 5432 and H. R. 8725 before a Subcommittee of the Committee on Public Works. H. R. 5431 would have forbidden the discharge of any industrial wastes into Niagara Frontier waters. H. R. 5432 would have required a permit from the U. S. Public Health Service for discharge of any industrial wastes into these waters. H. R. 8725 would have set concentration limits to effluent components, regardless of volume.

This pending hearing aroused industry to make an investigation which disclosed that these fish were largely nuisance types, alewives and gizzard shad, that they were not even dying in Niagara Frontier waters, but were perishing all over Lake Erie and being funneled into the Niagara River, that they are susceptible to death in great numbers from natural causes such as sharp temperature changes, and that no evidence of poisoning could be detected. Bruce Dickerson of Hercules Powder Company and the speaker, representing the Manufacturing Chemists' Association, presented this evidence and discussed other unrealistic features of these bills at the hearing. The Buffalo Chamber of Commerce submitted a statement supporting that position. None of the bills came out of committee. If any one of them had been enacted and enforced not only would industry and the people on the Niagara Frontier have been subjected to grave injustice, but a precedent for Federal control of water pollution would have been established.

Practically nothing has been heard about dead fish in this area since that time—over three years ago.

Immediately after classifying waters on the Niagara Frontier in 1954, the Water Pollution Control Board held interviews with industries and municipalities, which served as sources of pollution, on setting up pollution abatement programs. In September, 1955, the Board issued "Comprehensive Plan for Abatement of Pollution from Waters of Lake Erie (East End) - Niagara River Drainage Basins"in which the program for each industry and municipality was described.

That part of the program, pertaining to the Buffalo River, not only prescribed further waste treatment and investigations in cooperation with control agencies to disclose any additional needs for treatment, but also specified that each "company should participate with the other major industries on the Buffalo River in furthering consideration of the Buffalo River Pollution Abatement Project - Water System" and pointed out to each that if this project "is not constructed, a reappraisal of the requirements for further waste treatment by the company will be necessary."

Marked progress has been made in pursuit of this program. Additional

waste treatment operations have been established—notably a phenol recovery unit at Donner-Hanna Coke Corporation. Industry has cooperated with the personnel of a permanent laboratory of the I. J. C. which was established in Buffalo in 1956, and other collaborating governmental agencies, in investigating the need for further waste treatment as related to fish toxicity, tastes in water supplies from the Niagara River, etc. All companies installed equipment for sampling and National Aniline Division of Allied Chemical & Dye Corporation supplied laboratories for making several lengthy series of bioassays of effluents from the plants and of Buffalo River water which receives these effluents. Results and recommendations from this work have not yet been issued, but examination of the data does not indicate any serious problem.

In this connection, it should be noted that it is not sufficient to meet the standards of quality for the classified use of a segment of stream if the quality of that water impairs another segment of water with higher classification into which it flows. Accordingly, the problem for meeting the standards of quality for the classified use of the Buffalo River basin is not nearly as difficult as it is to prevent its impairment of the Niagara River waters for their higher classified uses. In other words, it may be necessary for water in the Buffalo River basin to be of higher quality than required for navigation which is its classified use.

Marked progress has also been made advancing the Buffalo River Pollution Abatement Project - Water System toward consummation. Up to 1956, no agreement was reached as to who should finance, build and operate the system. For several years, the Buffalo Sewer Authority seemed to be the proper agency, but it was finally decided that there were legal and financial obstacles which could not be overcome. Other agencies were considered without success. During that period the proposal was for the agency to charge industry for water at a rate which would amortize bonds in 25-30 years and cover operating costs. That long time commitment was another serious obstacle in view of the possibility that one or more plants might relocate in the interim and have no need for water to abate pollution in a stream to which it would not contribute.

Finally, in 1956 it was agreed that the city should finance, build and lease the plant to a corporation, the Buffalo River Improvement Corporation, to be formed by the five companies. The rental charge would be based on a 30 year amortization period, and the Corporation would meet such charge, as well as operating and maintenance expenses, from proceeds of sale of water to the five companies. In the 1957 Session of the New York State Legislature, an appropriate enabling act was enacted. Completion of the details of an agreement and lease with the city and the formation of a corporation remain to make this proposed project an actuality.

There are many other aspects of the problem and program for the Niagara area for other industries and communities on which marked progress is being made, but time does not permit discussion of these. Progress on solving the entire problem is reflected by this statement "Excellent progress has been made on all phases of pollution in Niagara boundary waters. We are confident that this progress will continue", which was reported by newspapers on April 6, 1957 to have been made by L. F. Warrick, Chairman. U. S. Section, Board of Technical Advisors to the I. J. C.

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LIQUID CONTENT OF GARBAGE AND REFUSE

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(Proc. Paper 1411)

SYNOPSIS

The optimum moisture (water) content for aerobic composting of organic wastes varies considerably with the type of wastes. Determination of the liquid content by the formula:

$$\% \text{ Liquid} = \frac{100\ (\% \text{ Moisture} + \% \text{ Lipids})}{(100 - \% \text{ Ash})}$$

(all values on a wet basis) is proposed as an analysis more universally applicable than moisture content.

The moisture or liquid content of the matter being composted is one of the most important factors in aerobic composting. In theory, moisture is needed to provide a very thin film of liquid over the organic particles to be decomposed by microorganisms. Water is required for the environment and the metabolic processes of the organisms. As water serves as a solvent or dispersion medium for all other constituents of protoplasm, it is the most abundant substance in living cells. Cellular absorption, secretion, diffusion, and excretion could not take place without water.(1) If an organic particle is completely dry, no decomposition will occur. If the particle has only the interior pores filled with water and the outside surfaces are relatively dry, the bacterial action will be slow or negligible. It is known that organic matter will not compost rapidly if the moisture (water) content is much below 40 percent (wet weight basis).

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Aeration is also essential to aerobic composting in order to supply the organisms with oxygen and to carry off the waste products of decomposition (primarily CO_2 and H_2O). If the void spaces are clogged with water or other liquid, the air-water interfacial surface is reduced and the benefits of aeration are largely lost. Oxygen and carbon dioxide diffuse through liquids so slowly that only small amounts are carried to or from organisms which are beneath the surface. Organisms living beneath a liquid surface will decompose organic matter largely by anaerobic rather than aerobic action, unless finely diffused air or oxygen is continuously sweeping through the liquid. Anaerobic decomposition is to be prevented or minimized because it is slow and produces foul odors. Without primarily aerobic action, temperatures of composting matter are low, resulting in poor moisture removal by evaporation and a possible degeneration of the condition due to greater water production than evaporation. Insofar as the effect on aeration is concerned, the presence of liquids other than water in the composting mixture will be as harmful as water, and may be more harmful. Although water holds only small amounts of free O_2 and CO_2 (5.6 and 580 ppm, respectively, at 122° F), it is a better solvent for these gases than other liquids which may be present in the compost.

There are two extremes of moisture or liquid content between which aerobic decomposition of solid wastes can occur. The mixture must have sufficient liquid for metabolic activity of the organisms but it must not have so much that aeration is prevented or hindered. Estimates by various workers of the optimum moisture content for aerobic, thermophilic composting of garbage or refuse vary from 40 to 70 percent and there is a wide discrepancy in these estimates.[2][12] The moisture content in such estimates is generally the water content in percent on a wet basis as determined by heat drying or, possibly, other methods such as Karl Fischer titration[2] or toluene distillation.[13] Examples of the wide range in optimum moisture content for mechanical composting are shown in table 1.

Table 1. Optimum Moisture Content for High-Rate Mechanical Composting of Three Types of Material.

Location	Material Composted	Moisture Contents %	
		Desirable range	Optimum
Savannah, Georgia[2]	Municipal refuse, non-compostables & some paper removed	55-69	60-65
East Lansing, Mich.[3]	Wrapped municipal garbage	55-60	57-58
Kobe, Japan[4]	Refuse, contains about 25% soil	Unknown (60-70 is too high)	About 50-55

It appears from the above that the moisture content by weight is not sufficient information to predict whether or not garbage or refuse will be decomposed readily by aerobic composting without knowing more about the raw materials. With some raw materials, the mixture will be too "wet" to compost properly at 60 percent moisture, while with others this moisture content may be optimum.

Moisture content of plain raw garbage (without paper) may be 70 to 80 percent as delivered to a plant. The garbage is dripping wet and will decompose largely by anaerobic, rather than aerobic, action unless the liquid content is reduced by some means. The percent of water in garbage may be reduced in two ways: (1) by removal of water, as drying, draining, filtering, centrifuging, etc., or (2) by addition of dry material, such as paper, straw, soil, leaves, etc. Actual removal of water may be expensive and may at the same time remove soluble materials of benefit to the composting process (in the cases of draining, filtering or centrifuging). The second method may, therefore, be more economical and satisfactory. Soil would be a poor dispersion medium for water because it is relatively non-absorbent and has a high density. Thus, soil might be harmful to the physical structure of the composting matter by causing compaction which reduces pore space and hinders aeration. On the other hand, paper is a good absorbent and it is also a waste material normally present in more than ample amount in refuse. Added paper, straw, leaves or similar organic material will increase volume as well as disperse the water content of garbage so that adequate aeration may be attained.

Factors Affecting Optimum Liquid Content for Aerobic Composting

The wide differences in optimum moisture content for aerobic composting of various types of garbage and refuse shown in table 1 are probably not due to erroneous observations but to the different structures and compositions of the mixtures being tested. Without having fairly complete physical and chemical analyses of a given mixture, it would be difficult to predetermine the moisture content for most rapid decomposition of that mixture. It appears that a combination of several factors including the moisture content are desirable to establish a "liquid" content which would take into account the type of materials to be aerobically composted. Thus, the "liquid" contents optimum for composting of several types of wastes might show a much smaller range of values than the range of water content values. The term "liquid" includes all free-flowing fluids, other than gases, at the temperatures reached during thermophilic composting, including moisture or water.

It is thought that three determinations should be considered in computing a "liquid" content of garbage or refuse to be composted: (1) moisture (water) content, (2) lipids content, and (3) mineral matter, or ash, content. The moisture content will be used as the basic factor because of the important roles of water in composting. Lipids are the greases, fats, oils and waxes. Many of the lipids or their decomposition products are liquid at normal composting temperatures and may be detrimental to aerobic composting by interferring with adequate aeration. Tests on ten batches of raw Savannah refuse as composted in laboratory units gave an average lipids content of 9.7 percent on a dry basis. As this refuse contains about 53 percent paper, it may be assumed that raw garbage without paper contains approximately 20 to 30

percent lipids on a dry basis. These values are appreciable when it is considered that lipids increase the liquid content without increasing the water content.

Mention has been made that soil may be added to garbage and will reduce the percent moisture therein but that such addition may not improve aeration. Refuse contains such inorganic materials as metals, glass, ceramics, ashes, and soil or dirt. These inorganics when added to garbage increase both total and dry weight of the mixture disproportionately and do not materially aid in absorbing the liquids or in increasing the liquid-holding capacity of the mixture. Therefore, the inorganic content or ash content should be deleted in the computation of the liquid content of garbage or refuse intended for aerobic composting.

Other factors of considerable importance to aerobic composting but not considered in the determination of liquid or moisture content are particle size and structure. These should perhaps be considered separately from any formula for liquid content. It should be stressed, however, that fine grinding of garbage or refuse destroys more of the cell structure of the organic materials and releases more of the liquids than coarse grinding. Thus, the optimum total liquid content for composting may be less for finely ground than for coarsely ground, but otherwise identical, materials.

Proposed Liquid Content Determination

It is suggested that the moisture content of garbage or refuse to be composted aerobically be modified by the addition of the lipids content and the deletion of the ash content of the mixture. It is proposed that the result be termed the "liquid content" and be expressed as percent of the wet weight. The proposed liquid content is defined as the percentage of water and lipids in terms of the wet weight of the mixture, less the ash content. The liquid content as proposed is calculated as follows, all analyses expressed as percent of the total (wet) weight of the material:*

$$\% \text{ Liquid} = \frac{100\ (\% \text{ Moisture} + \% \text{ Lipids})}{100 - \% \text{ Ash}}$$

The term (100 - % Ash) represents the percent volatile solids or, roughly, the percent organic matter.

The following tests are required for the determination of the liquid content:

Moisture—by oven drying, Karl Fischer, or toluene distillation methods
Lipids—by ether extraction
Ash—by combustion

A recent publication[14] presents the methods of analyses noted above as used at Savannah with the exception of the toluene distillation method.[15] (Drying at 50° C rather than at 100° C or higher, is recommended in order to avoid loss of volatile materials other than water. However, tests are being

*Normally only moisture is reported on a wet weight basis, while other constituents are reported on a dry weight basis.

conducted to determine whether 50° C or 100° C is better, not only for determination of moisture but also for subsequent tests, particularly for nitrogen, made on the oven-dried material.)

Sample Calculations

Following are sample calculations for the three mixtures given in table 1, using for the moisture content the average of values given in the column "optimum percent":

Savannah, Georgia

Material: Municipal residential refuse with non-compostables and some paper discarded. Estimated paper content 53 percent on a dry basis.

Water (moisture) = 62.5 percent (wet basis)

Lipids (ether extract) = 10 percent (dry basis) or 3.8 percent (wet basis)

Ash = 7% (dry basis) or 2.6% (wet basis)

$$\text{Liquid} = \frac{100\ (62.5 + 3.8)}{(100 - 2.6)} = 68.1\%$$

East Lansing, Michigan

Material: Municipal garbage, wrapped. Paper content is approximately 33% on a dry basis.

Water (moisture) = 57.5% (wet basis) (assuming that the moisture content has been reduced by drainage.

Lipids = 16.7% (dry basis)* or 7.1% (wet basis)

Ash = 10% (dry basis) or 4.25% (wet basis)

$$\text{Liquid} = \frac{100\ (57.5 + 7.1)}{(100 - 4.25)} = 67.5\%$$

Kobe, Japan

Material: Municipal refuse (domestic and light industrial). Contains approximately 25% soil and 25% paper, straw and wood on a wet basis.

Water (moisture) = 52.5% (wet basis)

Lipids = 3.0% (dry basis)** or 1.4% (wet basis)

Ash = 48.6% (dry basis) or 23.1% (wet basis)

$$\text{Liquid} = \frac{100\ (52.5 + 1.4)}{(100 - 23.1)} = 70.1\%$$

On the basis of average values for the optimum moisture contents given in table 1, the calculated liquid contents for the three types of raw material are shown in table 2.

*Estimate (based on 25% lipids [dry basis] in garbage portion)
**Estimate (based on 10% lipids [dry basis] in garbage portion)

Table 2. Comparison of Estimated Liquid Content with Optimum Moisture Content for Mechanical Composting.

Location	Type of Material	Optimum Moisture Content, %	Liquid Content %
Savannah, Georgia	Refuse	62.5	68.1
East Lansing, Mich.	Wrapped garbage	57.5	67.5
Kobe, Japan	Refuse with soil	52.5	70.1

Although the optimum moisture contents for the three wastes are widely different the estimated liquid contents of the wastes are nearly alike. Thus, the liquid content appears to place different materials which are to be aerobically composted on a more comparable basis than is indicated by the moisture values alone. The liquid content may, therefore, be a useful measure to evaluate not only moisture but other factors in solid wastes which indicate the potential for good or poor aerobic decomposition in mechanical composters. Liquid content may also be more valuable than moisture content analysis for predicting the course of aerobic decomposition in windrows, bins or cells where natural ventilation is relied upon rather than continuous mechanical aeration and/or mixing.

With plain raw garbage without any paper, soil or other matter, it has been indicated that the fresh material is too wet for satisfactory aerobic composting. Garbage alone might have lipids and ash contents of approximately 25 percent and 13 percent, respectively, on a dry basis. Assuming that the liquid content should be about 69 percent (see table 2), it may be of interest to compute an approximate moisture content for optimum composting (the lipids and ash contents above are converted to a wet weight basis):

Let X = percent moisture, expressed as a decimal.

$$69.0 = \frac{100\,(100\,X + [25.0\,(1.00 - X)])}{100 - [13.0\,(1.00 - X)]}; \quad X = 0.5305$$

It might be expected, therefore, that plain garbage should have a moisture content of about 50 to 55 percent for optimum aerobic composting if it contains lipids and ash contents of approximately 25 percent and 13 percent, respectively, on a dry basis (11.7% and 6.1% on a wet basis in this case). As previously discussed, the water content of raw garbage is usually much higher than 50 to 55 percent and means must be taken to lower moisture if garbage is to be composted under aerobic conditions in a short time. At San Diego, California,[5][16] drainage reduced the water content to about 60 percent but the pilot plant composting in outdoor piles still required about 90 days and as many as 23 turnings. At 60 percent moisture, one would expect the liquid content of the raw garbage to be about 74 percent, or still somewhat higher than the optimum values of 67.5 to 70 percent as shown in table 2.

Summary

Moisture is required in aerobic composting for the metabolic activity of microorganisms but moisture content should not be so great as to interfere with proper aeration. The optimum moisture content of mixtures being composted varies with the materials and particularly with the lipids and ash contents of the materials. Determination of the liquid content by the formula:

$$\% \text{ Liquid} = \frac{100\ (\% \text{ Moisture} + \% \text{ Lipids})}{(100 - \% \text{ Ash})}$$

(all values on a wet basis) is proposed as an analysis more applicable to the various types of wastes to be composted than the moisture (water) content. The liquid content formula does not include particle size of the solid materials which has an important bearing on the free liquid present.

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Paper 1422 October, 1957 SA 5

Journal of the
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CONTENTS

DISCUSSION
(Proc. Paper 1422)

Page

Design of Venturi Flumes in Circular Conduits, by Edwin A. Wells and Harold B. Gotaas. (Proc. Paper 928. Prior discussion: none. Discussion closed.)
by K. Fraschina 1422-3

Sedimentation Studies, by D. E. Bloodgood, W. J. Boegly, and C. E. Smith. (Proc. Paper 1083. Prior discussion: 1227. Discussion closed.)
by D. E. Bloodgood, W. J. Boegly, and C. E. Smith (Closure) . . 1422-9

Sanitary Engineering Education: ICA Assistance in Peru, by Marvin L. Granstrom. (Proc. Paper 1224. Prior discussion: none. Discussion closed.)
by Harold E. Babbitt 1422-11

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Discussion of
"DESIGN OF VENTURI FLUMES IN CIRCULAR CONDUITS"

by Edwin A. Wells and Harold B. Gotaas
(Proc. Paper 928)

K. FRASCHINA.[1]—The North Point Sewage Treatment Plant, San Francisco, Calif., is a primary treatment plant designed for an average dry weather flow of 65 mgd and a maximum wet weather flow rate of 150 mgd. The plant was placed in operation in December 1951.

Plant inflow is measured as the summation of flow in four Parshall flumes used to regulate velocity of flow in four grit tanks. Plant outflow is measured by a Palmer-Bowlus flume in a covered channel between the sedimentation tanks and the post-chlorination contact tank. The Parshall flumes are followed by a sewage lift station. As a consequence, plant outflow rate depends on sewage and sludge pumping rates, and varies from plant inflow rate accordingly.

The Palmer-Bowlus flume is designed for a flow range of 15-150 mgd. The flume is accurately constructed of smooth concrete to the dimensions shown in Figure 1. It will be observed that the upstream channel is trapezoidal rather than circular in shape. The theoretical rating curve was derived by trial and error solution of Equation (2). Dimensions and flow characteristics listed as essential by Wells and Gotaas are given below. The value of D is taken here as the width of the upstream channel, or 8.00 ft.

Throat length	0.88 D
Side slope, all sections	1:1
Base height	D/8
Entrance transition slopes	
Sides	1:6
Base	1:6
Terminal transition slopes	
Sides	1:5
Base	1:1 1/2
Distance from flume entrance to point of upstream depth measurement	0.09 D
Upstream channel slope	
1st 2' upstream of flume entrance	level
Balance	$< 0.1\%$
Velocity of approach, fps*	
15 mgd	1.5
150 mgd	5.0
Velocity head, max flow*	0.07 D
Submergence at 150 mgd**	85%

1. Supt., North Point Sewage Treatment Plant, San Francisco, Calif.

* From theoretical rating curve; flume not accessible for measurement.

** Ratio observed tailwater depth/d_n from theoretical rating curve.

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The flume differs from the design recommendations on page 928-30 in the following particulars:

1. The base height, D/8, slightly exceeds the recommended range D/10 to D/20 given for trapezoidal flumes.
2. The slope of the entrance transition, 1:6, is less than the recommended slope 1:3.

These differences appear to be too inconsequential to affect flume accuracy.

Flume Accuracy

The only means available for checking accuracy of the flume is by comparison with plant inflow measured in the Parshall flumes. Table 1 shows such a comparison as measured by daily average flow rates on 21 week days during July 1956. Column 1 gives sewage inflow measured by the Parshall flumes; Column 2 volume of sludge removed from the sedimentation tanks measured by the sludge Venturi meter; Column 3 sewage outflow measured by the Palmer-Bowlus flume; Column 4 sewage outflow measured as the difference between Columns 1 and 2; and Column 5 algebraic difference between Columns 3 and 4. A statistical test of the differences in Column 5 by "Students t Test" (1) gives a "t" value of 0.47. The probability of obtaining an equal or greater value of "t" is over 60% and it can be concluded that there is no statistically significent difference in the two methods of measurement. This is shown diagrammatically in Figure 2 in which the data in Columns 3 and 4 are plotted on arithmetic probability paper. All points fall on a single straight line, and both sets of measurement can be considered normally distributed with the same inherent variability. It is to be noted that errors of measurement by the primary measuring elements and their flow integrating devices are included in this variability.

It would be desirable to supplement the average daily flow readings given in Table 1 with instantaneous readings taken over the entire range of flow. Unfortunately, steady flow conditions in the lift pump sump cannot be maintained long enough for accurate measurements to be made. Nevertheless, influent and effluent flow charts (each readable to 1 mgd) seldom differ by more than 1 mgd over the range 15-100 mgd when the sump level remains relatively constant and sludge withdrawal from sedimentation is at a steady 0.9 mgd rate.

Accuracy of this Palmer-Bowlus flume can be considered to be:

1. Equal to that of the Parshall flumes.
2. Probably well within the limit of 3% found by Wells and Gotaas.

The flume responds promptly to changes in flow. A hydraulic jump is observable within or below the exit transition section under all conditions of flow. There is no evidence of solids deposition in the channel ahead of the flume at low flows down to 15 mgd. No maintenance has been required in the five years the flume has been in service.

REFERENCE

1. Youden, W. J., "Statistical Methods for Chemists," John Wiley & Sons, Inc., New York, 1951, p. 28.

TABLE 1

Volume, million gallons

Date	Inflow (1)	Sludge (2)	Outflow (3)	Col(1)-Col(2) (4)	Col(3)-Col(4) (5)
July 2, 1956	42.8	0.9	42.1	41.9	0.2
3	42.2	0.9	42.0	41.3	0.7
5	42.7	0.8	41.9	41.9	0.0
6	43.1	0.8	42.7	42.3	0.4
9	43.7	0.8	43.2	42.9	0.3
10	42.9	0.8	42.8	42.1	0.7
11	43.1	0.8	42.9	42.3	0.6
12	43.0	0.8	41.8	42.2	-0.4
13	43.4	0.9	42.4	42.5	-0.1
16	43.4	0.9	41.7	42.5	-0.8
17	43.1	0.9	42.0	42.2	-0.2
18	43.8	0.9	42.2	42.9	-0.7
19	42.7	0.9	41.7	41.8	-0.1
20	43.6	0.9	41.5	42.7	-1.2
23	43.2	0.9	41.9	42.3	-0.4
24	43.5	0.9	42.4	42.6	-0.2
25	43.7	0.9	42.4	42.8	-0.4
26	42.6	0.9	41.7	41.7	0.0
27	42.4	0.9	41.8	41.4	0.3
30	42.9	0.8	41.9	42.1	-0.2
31	43.0	0.9	42.5	42.1	0.4
Avg	43.1	0.9	42.1	42.2	-0.1

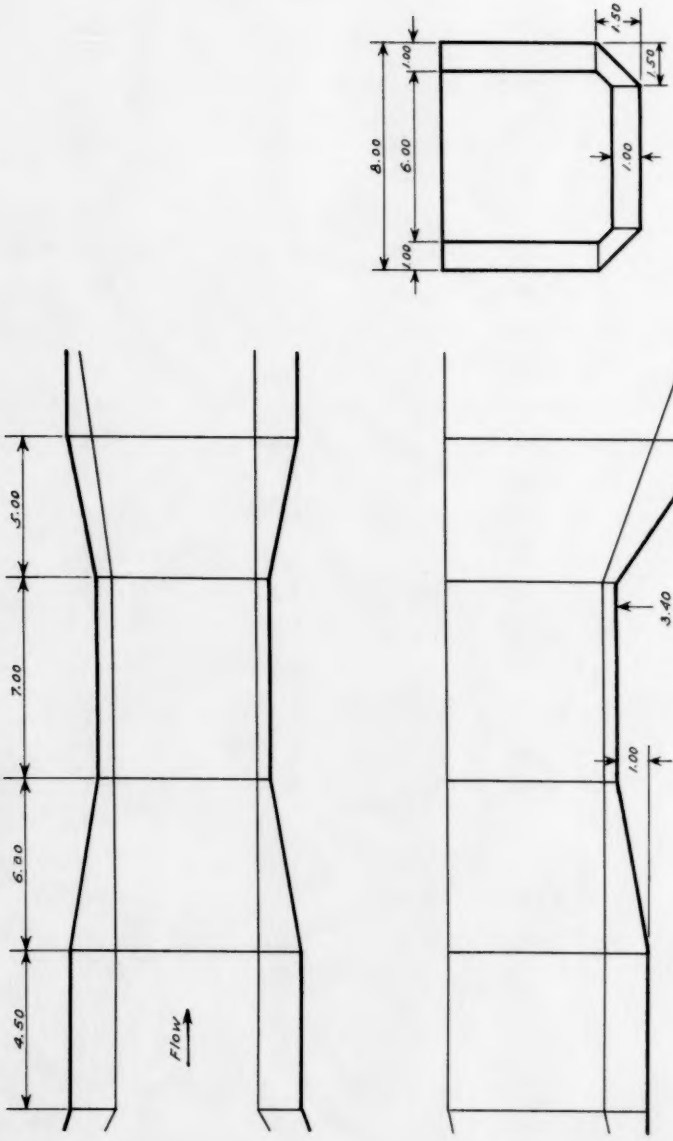

FIGURE 1

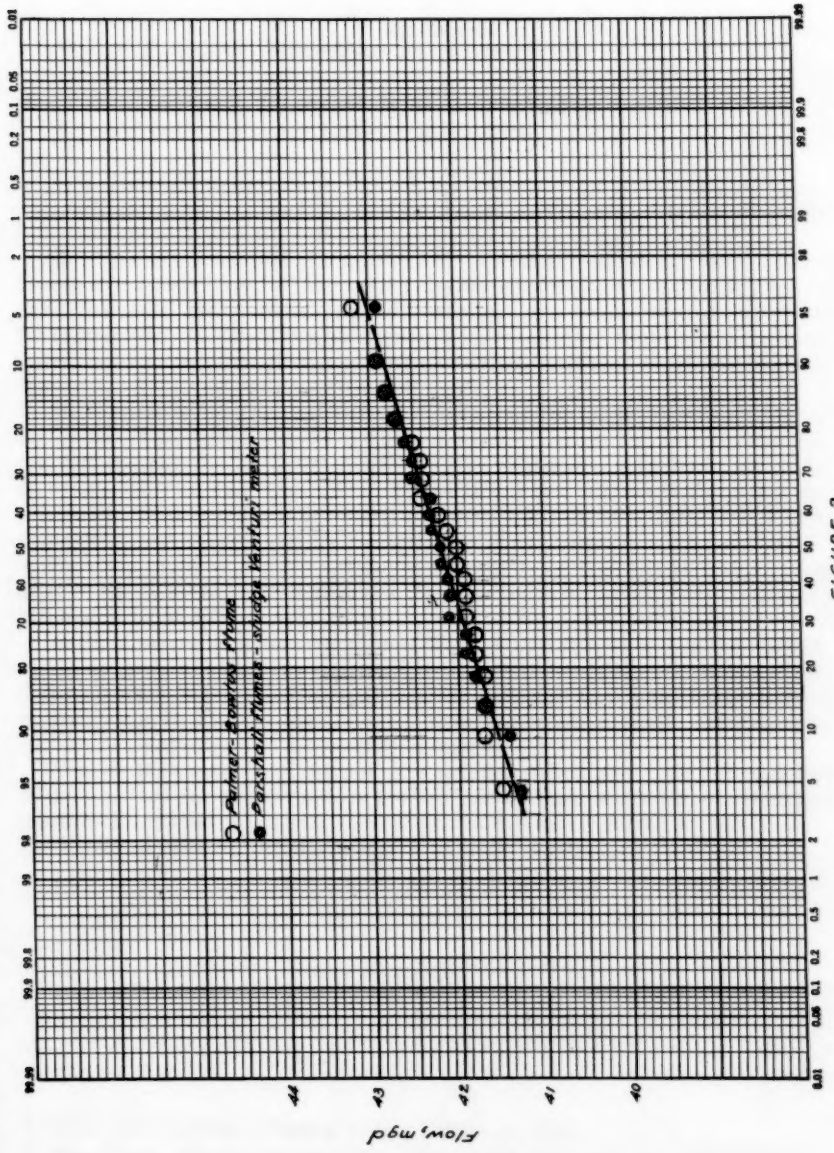
Palmer-Bowlus flume
Parshall flume - sludge venturi meter
flow, mgd
44
43
42
41
40

FIGURE 2

Discussion of
"SEDIMENTATION STUDIES"

by D. E. Bloodgood, W. J. Boegly, and C. E. Smith
(Proc. Paper 1083)

D. E. BLOODGOOD,[1] W. J. BOEGLY,[2] and C. E. SMITH,[3] J.M. ASCE.—
The discussion by N. Claes, H. Fischerstrom (1227-5) provided an interesting and valuable interpretation of data presented in the original paper.

Mr. Fischerstrom stated that since the hydraulic values for tests 1 through 35 are extremely good, all the tested basins should be well suited to prove the over-flow rate theory in the applied flow range and sediment concentrations. He further states, "It cannot be expected therefore that there will be any great difference between the chosen basins or that any limiting values for application of the Hazen theorem will be obtained."

Mr. Fischerstrom has indicated explanations for slight differences from the expected performance of the various basin sizes on the assumption that the suspensions are all truly identical. The suspensions were not all truly identical and this was observed by conducting a settling rate determination in a settling column on the suspension for each test run. The differences in the suspensions as determined by the settling column tests were thought to be sufficiently great to explain the slight difference from the expected performance of the various basin sizes, but the comments of Fischerstrom appear to offer additional explanations.

In the discussion it was mentioned that the specific weight of the suspension was probably not very different from that of the effluent. Although no determination of the specific weight of the suspension was made, there was no indication that it was significantly higher than the effluent. Density currents were not observed in the basins studied.

The writers agree that the use of a sediment such as Celite 545 as a possible standard for sedimentation studies has definite merit but would recommend that a standard settling column procedure be employed to insure that the material used by various workers is truly similar.

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2. San. Engr., Health Physics Div., Oak Ridge National Lab., Oak Ridge, Tenn.; formerly Research Asst., Purdue Univ., Lafayette, Ind.
3. Regional San. Engr., Chain Belt Co., Philadelphia, Pa.; formerly Research Asst., Purdue University, Lafayette, Ind.

Discussion of
"SANITARY ENGINEERING EDUCATION: ICA ASSISTANCE IN PERU"

by Marvin L. Granstrom
(Proc. Paper 1224)

HAROLD E. BABBITT,[1] M. ASCE.—The applicability of some of the author's statements concerning conditions of sanitary engineering education in Peru to conditions in Brazil is striking. Some of his sentences would be equally correct if the name Brazil were substituted for Peru. There are, however, sufficient differences to show that the conditions of sanitary engineering education in Brazil are encouraging and that the future for educators and for practitioners in the field is promising. The author mentions the graduate school of sanitary engineering at the Institute of Hygiene in São Paulo. This school is outstanding in the quality of its teaching and in the qualifications of its staff. Most of them have studied sanitary engineering in the United States. It is to be noted, however, that many other schools in the country are teaching sanitary engineering subjects. A post-graduate course in the field was inaugurated in the College of Engineering of the University of Minas Gerias in Belo Horizonte in 1955. Professor Lincoln Contentintino, an alumnus of Harvard University, was the moving spirit in starting this course. This school is sending, under cooperation with ICA, sanitary engineering students for advanced study at schools in the United States. Two Brazilian engineers received masters degrees in sanitary engineering this year at Johns Hopkins. One will return to Brazil as a member of the teaching staff at the University of Minas Gerias and the other will go to the University of Pernambuco at Recife. Alumni of Harvard, Johns Hopkins, North Carolina, Michigan, Minnesota, and other North American universities are astonishingly numerous on the teaching staffs of engineering colleges throughout Brazil.

Undergraduate courses in sanitary engineering are taught in more than fifteen colleges of engineering in Brazil. At least nine of these schools, located in State capitals, have on their staff at least one member who has attended a school of sanitary engineering in the United States and, in some schools, one or more of the staff members has studied sanitary engineering in Europe. Sanitary engineering courses in Brazilian colleges of engineering are administered by the Department of Civil Engineering, much as they are in the United States. The courses are taught to undergraduates principally by men who have not specialized in sanitary engineering. There is no special curriculum nor diploma in the subject. Courses in chemistry are the same as those to which all civil engineering students are exposed. Information in the biological and sanitary sciences is conspicuous mainly by its absence. In one or two schools there is interchange between Departments in some fields. For example, bacteriology is offered to students in engineering by the Medical School in the University of Parana at Curitiba.

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1. Consultant, Brown and Caldwell, Cons. Engrs., Seattle Metropolitan Sewerage Area, Seattle, Wash.; recently San. Eng. Educational Consultant, ICA, Brazil.

An outstanding handicap under which all engineering education suffers is the lack of textbooks and of professional periodical literature. Engineering literature published in Portuguese is limited, and the relatively small number of engineers who read Portuguese does not attract publication in this language. A result is that there are few independently produced publications in Portuguese. Most such books are subsidized by governmental units for their special purposes. Some teachers prepare mimeographed (or similarly reproduced) notes, called apostilos, which may be produced at their own or the school's expense and may be given to or sold to students. Foreign-language books and periodicals dominate the educational field. Most teachers, upper-level undergraduates, and advanced students speak or read English, in addition to one or more other foreign languages. Bilingual ability is far wider spread among students in Brazil than it is in the United States.

Interest and knowledge of sanitary engineering is being maintained and promoted among sanitary engineering educators through biennial meetings of a group the nucleus of which is composed of one or more representatives from each college of engineering in the country which teaches the subject. This group has been meeting biennially since 1954, under the auspices of the Ministry of Education, which underwrites some of the expenses, and with the cooperation and sponsorship of the Servicio Especial de Saude Publique, familiarly known as SESP. The latter is a bureau of the Institute of Inter American Affairs and of ICA. The educators attending the meeting conduct a one-or-two-week seminar for the exchange of professional information and to discuss educational problems. It met in São Paulo in 1954, in Salvador in 1956, and is planning to meet in Belo Horizonte in July, 1958. It has served as an impetus to sanitary engineering education in Brazil. Those associated with it are highly enthusiastic over its results.

It is relatively easy to interest some students and practitioners in sanitary engineering subjects. This is demonstrated, in part, by the fine attendance at "short courses" being offered at such schools as the University of Rio Grande do Sul in Porto Alegre, at the University of Parana at Curitiba, and the University of Minas Gerias at Belo Horizonte. It is not so easy, however, to influence undergraduate students to specialize in sanitary engineering. As an undergraduate student he is somewhat of a ward of the government which pays for his education. When he receives his diploma he is eligible to practice professional engineering without further study or experience. However, his principal opportunities for the practice of sanitary engineering will be with a public works division of a governmental bureau interested in all branches of civil engineering, but not especially in sanitary engineering. Despite the great needs in Brazil the employment of specialists in sanitary engineering is not yet sufficiently general to promise a living to a young engineer confining himself to that field. The major rewards of employment in sanitary engineering are most likely to come to those who are able through their own resources, through their favorable location or employment, or through other opportunities to pursue post-graduate or in-service studies in the field.

The author's remarks concerning Peruvian part-time lecturers; laboratory teaching and facilities; field training and extension work; holidays; lengthy examination periods; and nonchalant attendance are applicable to many but not to all engineering colleges in Brazil. Programs and curricula are closely adhered to. This is due, in part, to the fact that all schools, although operated by the State, are supported partly or entirely by Federal

funds, and the Federal Government watches to see that it is getting its money's worth.

An encouraging aspect for the future of all engineering education in Brazil is the ambitious building program under way. Imposing, reinforced concrete buildings are being erected for colleges of engineering in all but one of the engineering schools that have been teaching civil engineers for more than five years. The buildings in Rio de Janeiro, in Salvador, and in Belo Horizonte are already far enough advanced to be imposing. Five new colleges of engineering are offering courses in civil engineering involving sanitary engineering subjects. No engineers have been graduated from these schools yet because the length of the engineering curriculum is five years and none of the new schools is that old. The situation in Brazil is such that the spread of knowledge of sanitary engineering subjects is increasing and that the prospect for the future of sanitary engineering education is bright.

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SETTLING BEHAVIOR OF WASTE SUSPENSIONS

Vaughn C. Behn,* J.M. ASCE
(Proc. Paper 1423)

SYNOPSIS

For many years the settling behavior of suspensions has captured the interest of workers in a number of fields. As a natural consequence there is available an extensive literature on the subject. The purpose of this paper is to bring together some of the available theories from the point of view of application in the field of waste treatment.

The qualitative mechanism of a settling slurry is set forth with consideration given to the experimental equipment used to observe such behavior. The means by which data from such equipment has been analyzed quantitatively for two important phases of settling is delineated. These two phases include the hindered or constant-rate settling zone, and the compression zone. In the latter instance previously unpublished work by the author on the analogy between the compression zone and soil consolidation is described.

The paper concludes with a discussion of the Kynch theory, which does not depend for its application on the restriction of settling regimes into zones. Application to a sewage sludge is demonstrated.

INTRODUCTION

The settling properties of suspensions become directly of interest in that phase of the waste treatment known as sludge thickening. According to the suggested nomenclature of the field, the term thickening is applied to the reduction of moisture content of a semi-liquid mass by settling in a type of sedimentation tank usually equipped with bottom scrapers.(1) The essential reason for which sludge thickening is undertaken is to reduce the volume of sludge prior to dewatering, transport for disposal, and occasionally before digestion.

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An understanding of the important process of thickening is contingent upon the knowledge of how settling slurries behave. The frequent appearance of thickening as a waste treatment process merits detailed consideration of the theories as to the mechanism of sludge settling.

Mechanism of Sludge Thickening

A qualitative discussion of the mechanism of settling suspensions, should in all probability commence with the work of Coe and Clevenger, who are generally credited with the first important description of this process.(2) These writers suggested that the continuous thickening of metallurgical slimes occurs in four separate zones. The uppermost zone is a layer of (relatively) clear water. Directly beneath this zone is one containing flocculated material of uniform consistency settling at a uniform rate. Finally the settling material passes through a "transition" zone into a "compression" zone in which all particles are in mutual contact. These four zones as Coe and Clevenger depicted them are shown in Figure 1.

Two alternatives were noted in this pattern of zoning, according to the extent of the transition zone. This zone, which is of variable composition, may either be narrow or, in other cases, so great as to exist to the exclusion of the constant composition zone above it.

According to Coe and Clevenger, when a suspension is allowed to settle quiescently in a container, the interface between the clear liquid and suspension first falls at a uniform rate. Simultaneously, a compression zone builds up from the bottom of the container. After a period of time, the rate begins to diminish, indicating that the interface has reached the top of the transition zone of variable composition. The decline in settling rate continues. When the interface reaches the top of the compression zone further fall results from a consolidation of the suspension. A suspension which enters immediately into a zone of variable composition would not show the constant rate period.

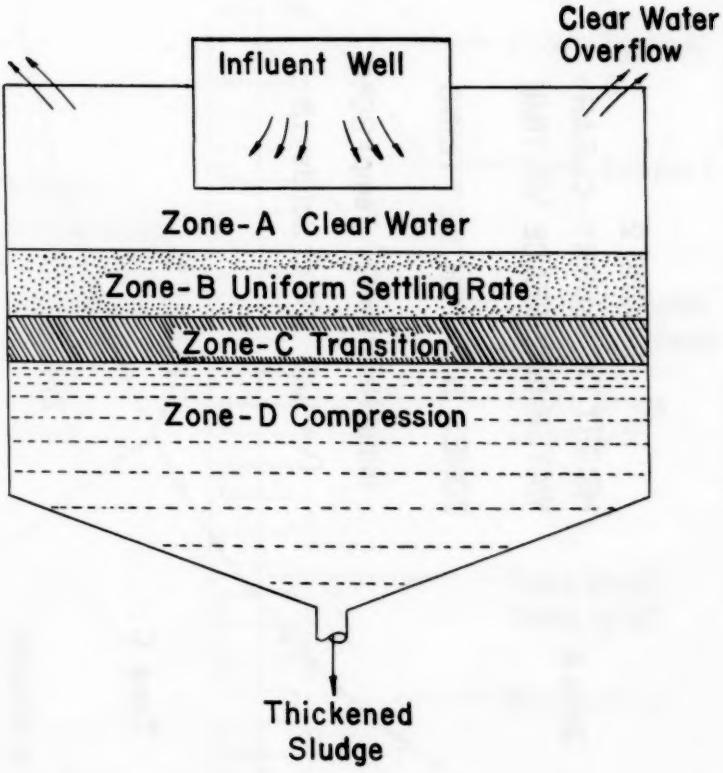
Application of Coe and Clevenger's analysis to an actual batch settling rate test may serve to demonstrate their conclusions. Figure 2 shows the relationship of the height of clear liquid-slurry interface versus time for a suspension of deaerated, digested sludge. The height of the interface or the conclusion of the constant rate period of fall marks the boundary of Zone B, while the height at which the sludge enters the compression zone, Hc, marks the beginning of Zone D. (The basis for estimating the latter is described below under the section headed COMPRESSION ZONE.) The slight lag in settling noted at the beginning of the test has been attributed to coagulation.(3) The settling column used to obtain the data of Figure 2 was equipped with rakes throughout the settling zone as shown in Figure 3.

Rakes are included in such a scheme, since on a qualitative basis they are perhaps the most important development since Coe and Clevenger's analysis. This was first demonstrated by Bull and Darby(4) and subsequently verified by others including Kammermeyer(5) and Comings.(6) The value of a slowly rotating rake during the batch settling of digested, deaerated sludge is shown in Figure 4. This demonstrates clearly that the rakes hasten the rate of fall of the clear water-slurry interface. Interestingly enough, the influence of the rake, which extended the entire height of the settling column, is noted from the onset of the experiment.

FIGURE I

ZONES IN A CONTINUOUS

SLUDE THICKENER



After Coe & Clevenger

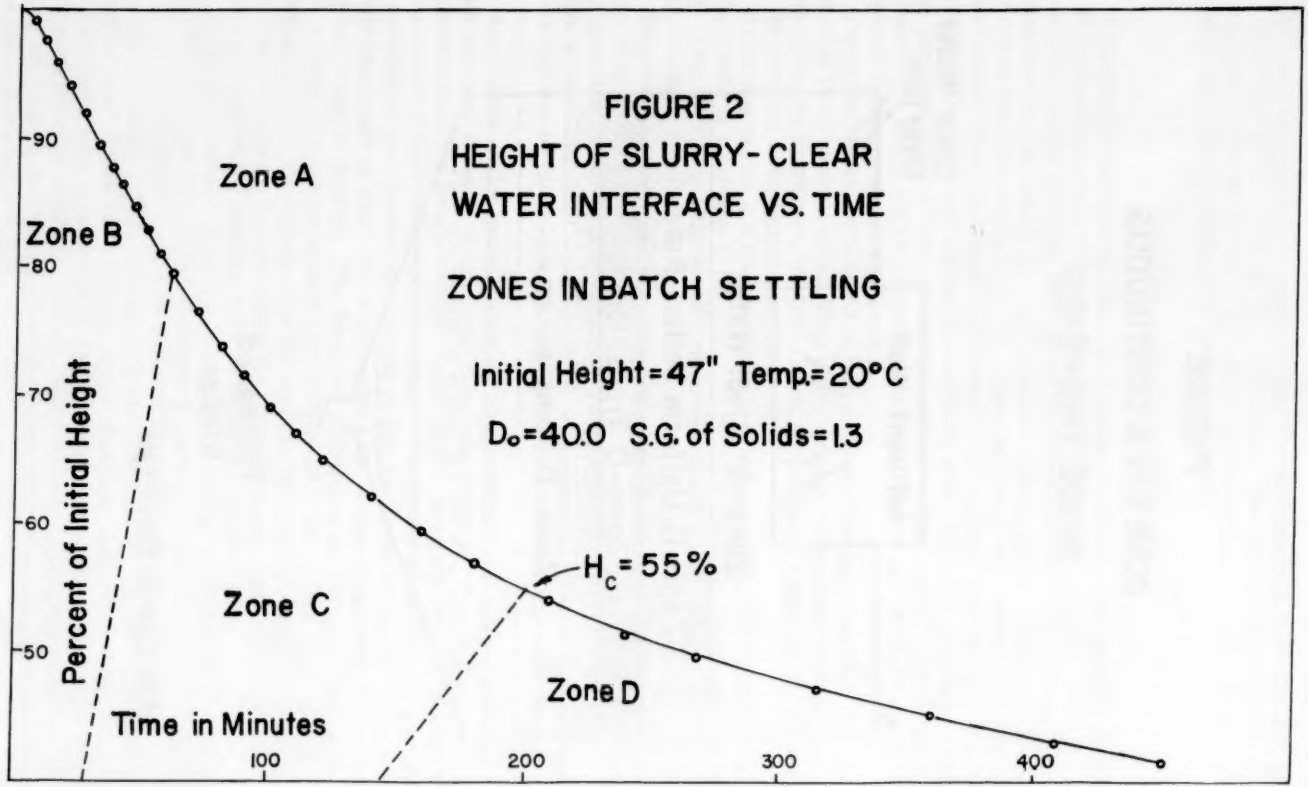
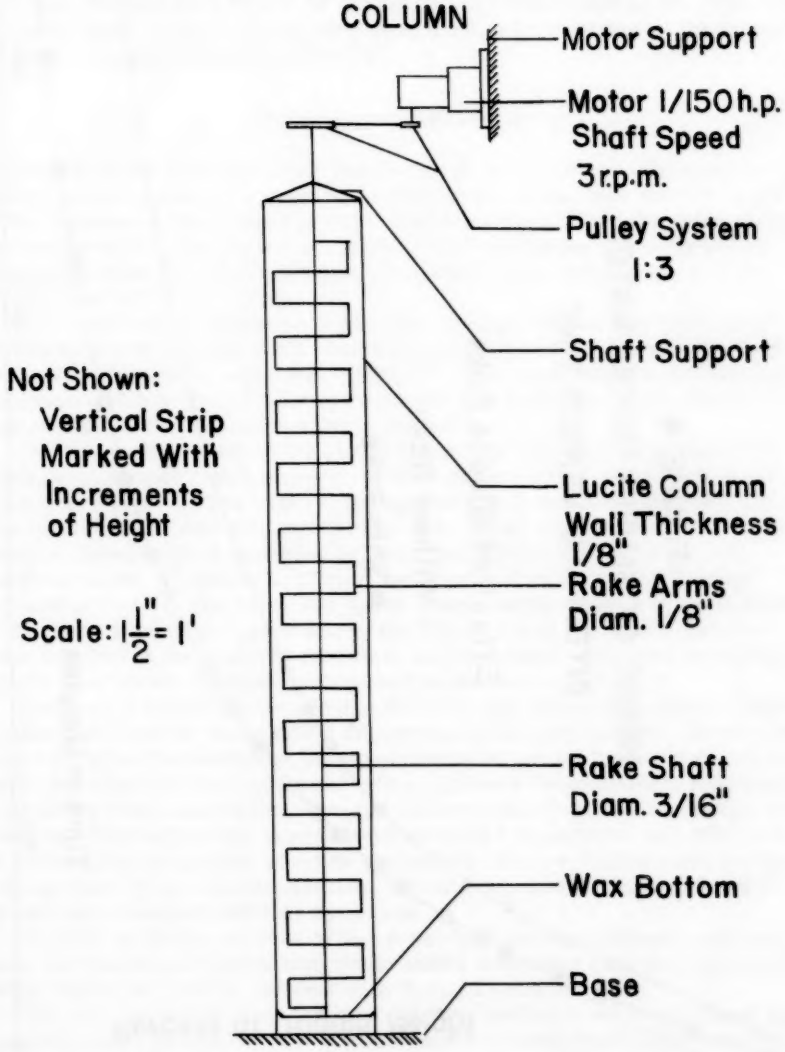


FIGURE 2
HEIGHT OF SLURRY- CLEAR
WATER INTERFACE VS. TIME
ZONES IN BATCH SETTLING
Initial Height = 47" Temp. = 20°C
D_o = 40.0 S.G. of Solids = 1.3
Zone A
Zone B
Zone C
Zone D
H_c = 55 %
Percent of Initial Height
Time in Minutes
90
80
70
60
50
100
200
300
400

FIGURE 3
20 LITER SLUDGE THICKENING COLUMN



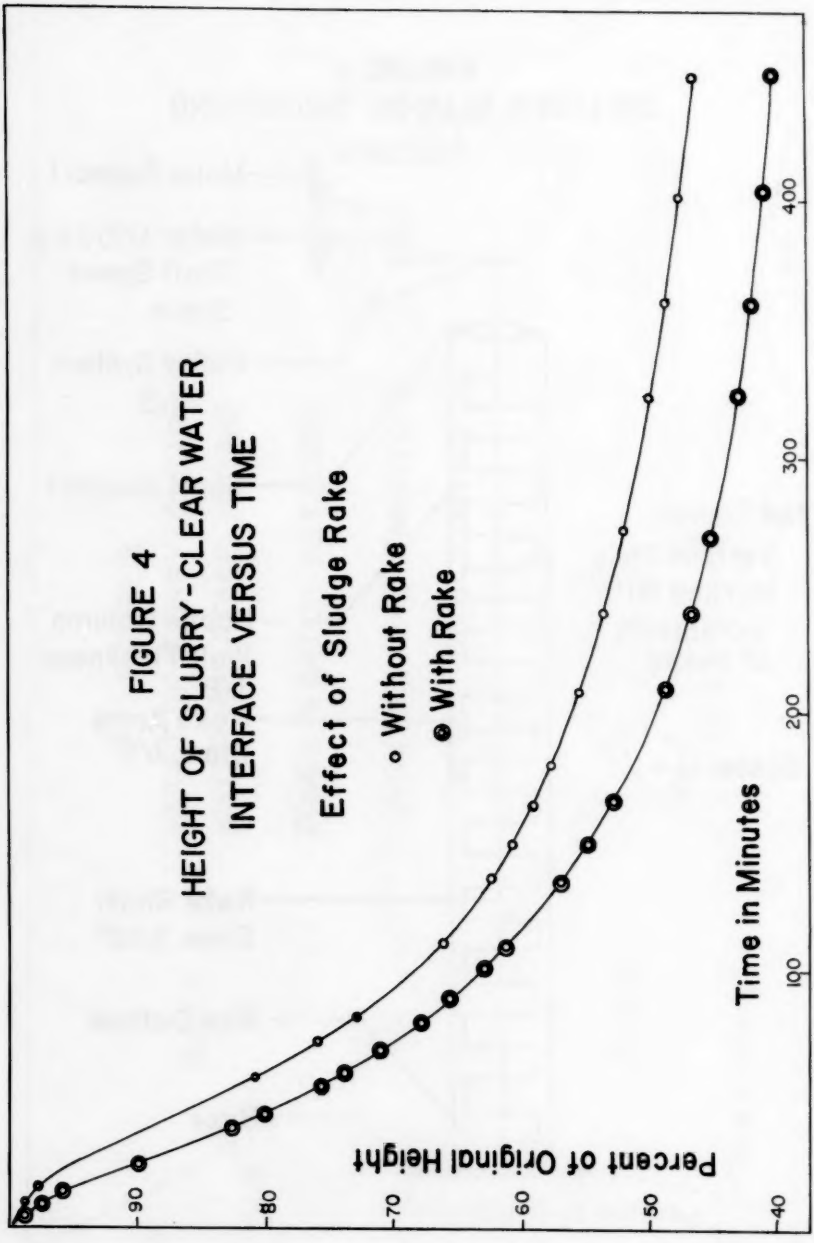


FIGURE 4
HEIGHT OF SLURRY-CLEAR WATER
INTERFACE VERSUS TIME
Effect of Sludge Rake
○ Without Rake
● With Rake
Percent of Original Height
90
80
70
60
50
40
100
200
300
400
Time in Minutes

Another useful way to present the Coe and Clevenger zone scheme is by considering the concentration gradient in a continuous thickener as measured vertically. Based on the work of Comings[6] and George,[7] the hypothetical concentration gradient should be that shown in Figure 5 for a sludge having characteristics similar to that depicted in Figure 2.

These developments do not, of course, explain quantitatively the behavior of suspensions. Prior to presenting such work, a brief review of experimental equipment used should be in order.

Experimental Equipment

Coulson and Richardson state that the chief factors which influence the rate of sedimentation of a given suspension in a vertical tube are the height of the suspension, the diameter of the containing vessel, and the volumetric concentration.[8] The writer would add to this listing the viscosity of the suspending medium, the rheological properties of the suspension, and the presence or absence of rakes.

With regard to the diameter of the tube, Kammermeyer has given experimental evidence to support his contention that a minimum diameter of 1.57 inches is sufficient to avoid wall effects.[5] Coe and Clevenger recommend a minimum of 2.5 inches.[2] George suggests that a 4" diameter column 30" high is satisfactory for batch settling tests.[7]

The writer, in a study of the sludge thickening operation in sewage treatment, used a stock 6 inch diameter plexiglass tube fitted with a rake made from 1/8" wire.[9] The rake, which operated at 1 rpm was patterned after that used by Work and Kohler.[10] The rake speed was selected as a compromise between the 4 rpm used by Work and Kohler,[10] the 2 rpm of Kammermeyer,[5] and the 1/12 rpm used by the Dorr Company Testing Laboratories.[11] The latter low speed was probably adapted to avoid undue undulation of the clear liquid-slurry interface. Using the 5 inch diameter rake selected in the writer's research, the peripheral velocities at the higher rpm's were closer to those encountered in commercial practice.

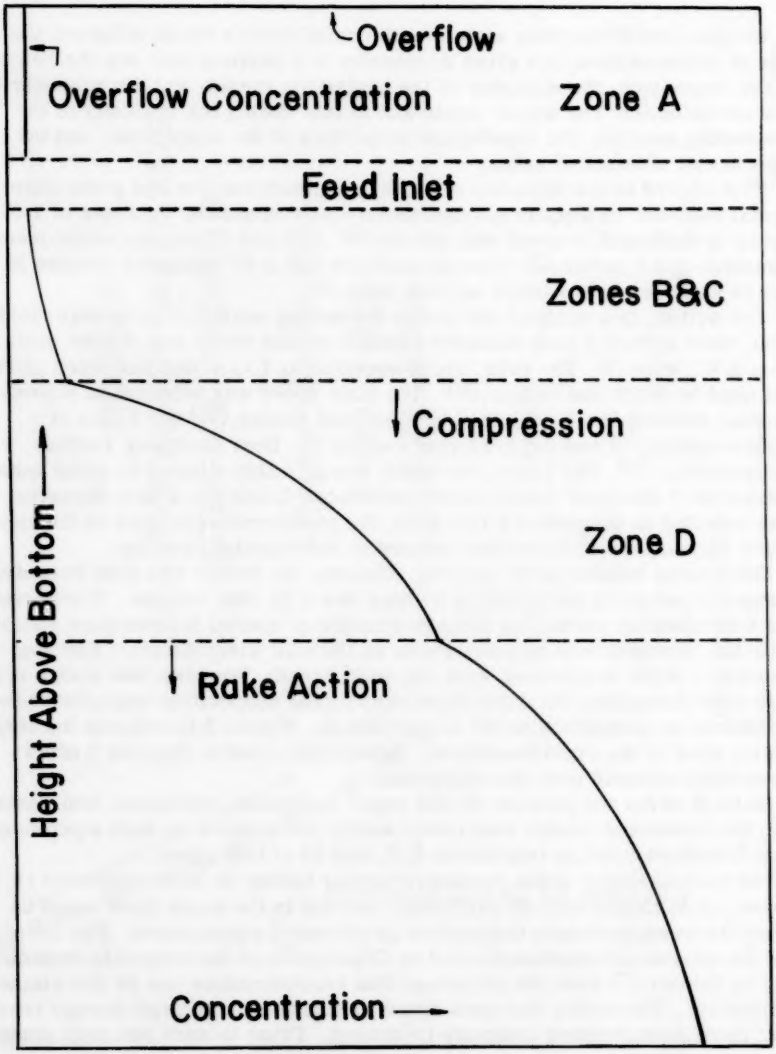
Concerning heights of the settling columns, the writer was able to control changes of height by using both a 20 liter and a 10 liter column. Temperature was controlled by conducting the experiments in special temperature rooms, while the viscosity was measured with an Ostwald Viscosimeter. Rheological properties of the suspension were not determined. However, the sludge rakes were used throughout the experimentation on the supposition that effects due to rheological properties would be minimized. Figure 3 illustrates the larger column used in the experimentation. Results depicted in Figures 2 and 4 above were obtained with this equipment.

While it is not the purpose of this paper to discuss continuous sedimentation, the interested reader may obtain useful information on such equipment from literature cited in references 6, 7, and 12 of this paper.

The type of slurry under consideration for testing in such equipment is, of course, quite important. Of particular interest in the waste field would be either the sewage sludges themselves or chemical precipitates. The latter, such as the calcium carbonate used by Comings[6] or the copper hydroxide used by George,[7] have the advantage that concentrations can be determined by titration. The writer has used digested sludge from a large sewage treatment plant incorporating complete treatment. Prior to each run such sludge

FIGURE 5

HYPOTHETICAL CONCENTRATION GRADIENT IN CONTINUOUS THICKENER



was degasified under at least 25" vacuum.

Alternatively, many workers have developed homogeneous suspensions of discrete particles. These have been found useful in studying the phenomenon of hindered settling, which is discussed in the following section. Reference to the literature cited in the section may be useful for those considering such suspensions.

Hindered Settling

As stated previously, a suspension of slurry in a vertical tube will usually settle in such a manner that the interface between clear water and slurry will first fall at a constant rate. The close proximity of the particles leads to a rate of fall less than that predicted by Stokes Law and is sometimes referred to as hindered settling.

Strictly empirical relationships for this phase of the settling process have been developed for specific suspensions by workers such as Kermack, McKendrick and Ponder,(13) and Boutaric and Roy.(14) Other workers, including Egolf and McCabe,(15) and Robinson(16) have developed semi-empirical formulae by simply modifying Stokes Law for the terminal velocity of a particle.

Robinson's equation has enjoyed the interest of a number of workers, while application of the equation has in the past been discussed in standard introductory chemical engineering tests.(8,17,18) For that reason an examination of the equation is in order.

Robinson proposed

$$\frac{dH}{dt} = \frac{k' d^2 (\rho_s - \rho_c)}{\mu_c} \qquad (1)$$

Symbol	Description	Dimension
H	Height of Sludge Column Slurry interface	L
t	time	T
k^1	constant	LT^{-2}
d	average particle diameter	L
p_s	density of particles	ML^{-3}
p_c	density of particles	ML^{-3}
μ_c	viscosity of suspension	$ML^{-1}T^{-1}$

Despite its past application, the Robinson equation is subject to severe restrictions for use with suspensions found in waste treatment. When dealing with suspensions of flocculent, heterogeneous particles both the value d and (p_s-p_c) are questionable entities. With discrete, uniform, particles these quantities have more significance since the particle diameter and the fractional volume of dispersion medium, e, can be determined. The latter can be used to determine (p_s-p_c) if the density of the particle, p_s, and the density of the dispersing medium, p, are known since;

$$(\rho_s-\rho_c) = \rho_s - (\rho_s(1-e) + \rho e) = e\,(\rho_s-\rho) \qquad (2)$$

An additional and important problem offered by the Robinson equation is the bulk viscosity of the slurry μ_c. Several authors have noted that this will change with the concentration of the slurry itself. Nevertheless, for a specific concentration Coulson and Richardson[8] suggest that the equations of Einstein and Vand may be used to determine μ_c. Actually, the question is further complicated by the non-Newtonian behavior of many sludges whose viscosity at any given concentration will vary with the shear rate. Since sewage sludges are in this category their rheological properties must be of importance.[19,20] Possibly it is in this area that the reason for the beneficial assistance from sludge rakes may be demonstrated.

While Robinson merely altered Stokes Law in its final form, other workers have modified the law in its development. Such work frequently takes a final form

$$\frac{v}{v_c} = f(e) \tag{3}$$

Where v is the settling velocity of a particle according to Stokes Law, v_c is the hindered settling velocity, and f(e) is a function of e, the fractional volume of dispersion medium (dimensionless).

Steinour,[21] for example, finds $f(e) = e^{2}10^{-1.82(1-e)}$ for small uniform spheres, while Fair and Geyer[22] suggest $f(e) = e^{4.3}$ for a suspension of discrete particles. Lapple[23] reports that Burgers proposes $f(e) = 1 + 6.875(1-e)$ for dilute suspensions, while Lewis and Bowerman[24] suggest a power function of e.

Comings, Pruiss and DeBord[12] utilized the relationship $\frac{v}{v_c} = \frac{\mu \cdot e}{\mu_c}$ derived from equation (1), equation (2), and Stokes Law. μ is the viscosity of the dispersing medium, and μ_c the slurry viscosity.

A somewhat different approach was used by McNown and Lin,[25] starting with the basis that the ratio of hindered to unhindered settling rate is a function of the concentration and Reynolds number, these workers show that as a first approximation

$$\frac{v}{v_c} = 1 + 1.3\,\frac{d}{s} \tag{4}$$

Where d = particle diameter and s = spacing between particles.

The experimental work of McNown and Lin is to a certain extent typical of other work reported in this section in that suspensions of discrete particles were used. The development in terms of a terminal settling velocity of a single particle and the fractional volume of dispersing medium stems from the ability to measure such factors quantitatively. Unfortunately, however, the heterogeneous suspensions of flocculent materials encountered in waste treatment do not lend themselves to such analysis so that the application becomes unsuitable.

Nevertheless, approaches to the analysis of the settling behavior of such suspensions are available. These differ somewhat from the work presented in this section in that they do not, generally speaking, restrict themselves to any special zone such as that of constant rate fall (hindered settling). Prior to presenting those theories which are of interest from a unifying standpoint, the second important zone, that of compression, is discussed.

Compression Zone

After the particles of a suspension are in mutual contact further fall bears little relationship to Stokes Law for the terminal velocity of a particle. Much of the work done on this zone has been in terms of the zone as a separate entity.

One of the most significant early contributions is that of Rollason[26] who showed that the falling rate of the interface in the last stages of compression is logarithmic. Egolt and McCabe[15] have also noted this behavior, while Roberts[27] developed an empirical formula for analyzing the compression zone as follows:

$$(D-D_\infty) = (D_o - D_\infty)\, e^{-kt} \tag{5}$$

Symbol	Description	Dimension
D	Dilution Factor at time t, weight of fluids divided by weight of solids	None
D_O, D_∞	Dilution Factor at time zero and infinity	None
k	Constant	T^{-1}

Qualitatively, the compression zone has often been noted, as analogous to the consolidation of soils. Work and Kohler[10] have noted this analogy, while Stein[28] has stated the matter explicitly.

> There is a similarity between the problem of compaction of sludge and of consolidation of clays as found in soils mechanics problems.

In 1953, the writer developed what is believed to be the first quantitative analysis of the relationship between soils consolidation and sludge thickening.[9] The concept involved is that of flow from the compressing sludge as governed by the laws of flow through porous media. The driving force is the "excess" hydrostatic head caused by the action of gravity upon the sludge mass. These considerations resulted in the equation:

$$\frac{K(\rho_s - \rho) g\, H_c}{w} \cdot \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \tag{6}$$

Symbol	Description	Dimension
$\frac{K\,(ps-p)_g Hc}{w}$		$L^2\,T^{-1}$
K	overall permeability constant	$L\,T^{-1}$
p_S	density of solids	ML^{-3}
p	density of suspending medium	ML^{-3}
w	unit weight of suspending medium	$ML^{-2}T^{-2}$
g	acceleration due to gravity	LT^{-2}

Symbol	Description	Dimension
u	"excess" hydrostatic pressure	$ML^{-1}T^{-2}$
z	Direction parallel to axis of travel of solids	L
t	time	
Hc	height of which sludge goes into compression	L

The solution of equation (6) for specific boundary conditions and in terms of more usable quantities gave the following equation

$$\log (D-D_\infty) = Kt + \log (D_o - D_\infty) \tag{7}$$

This is identical (except for logarithmic base) with the equation (5) suggested by Roberts except that now the constant k is defined:

$$K = \frac{K (\rho_s - \rho) g}{H_c w} \tag{8}$$

Now the permeability constant K is known to vary for a given soil sample directly with w and inversely with the viscosity of the liquid medium.(29) The implication is then that k in the above equation will vary inversely with Hc and μ. As explained in the previous section on experimental equipment, such variables may be altered easily in the laboratory. The writer was able to show to his own satisfaction that the behavior predicted by the theory can be demonstrated quantitatively.(9)

Since an illustration of the application of the technique may be of interest, the rate of fall of a slurry of deaerated, digested, sewage sludge is shown in Figure 6. This figure depicts the interface fall for two identical sludges at 20°C in a 10 liter and a 20 liter sludge column, marked as experiments B and A respectively. The columns are those described in the previous section on experimental equipment (Figure 3).

The data of Figure 6 are converted for use in equation (7) by use of the specific gravity of the sludge solids and the original concentration, since the dilution factor D equals volume of slurry, V, minus volume of solids divided by weight of solids, W. This may be converted to the form

$$D = \frac{V}{W} - \frac{1}{s.g.} \tag{9}$$

Where s.g. equals the specific gravity of the solids.

When V assumes its initial value v_o then D = Do, the Dilution Factor at time zero. The dilution factor at any time can then be found by multiplying $\frac{Vo}{W}$ times the height of the slurry interface (fraction of original height) and subtracting the inverse of the specific gravity. A log log plot is made to fit the data to equation (7). This requires an estimate of D_∞, by trial and error. The settling data of Figure 6 are thus plotted in Figure 7. In this experiment the straight line relationship existed throughout both runs and the assumption is made that each column was in compression at the outset of the experiment. In other experiments the curve may depart from a straight line at the beginning of the experiment. The point of departure is assumed to be the time at which the slurry reached the critical height. Still other data may depart from the

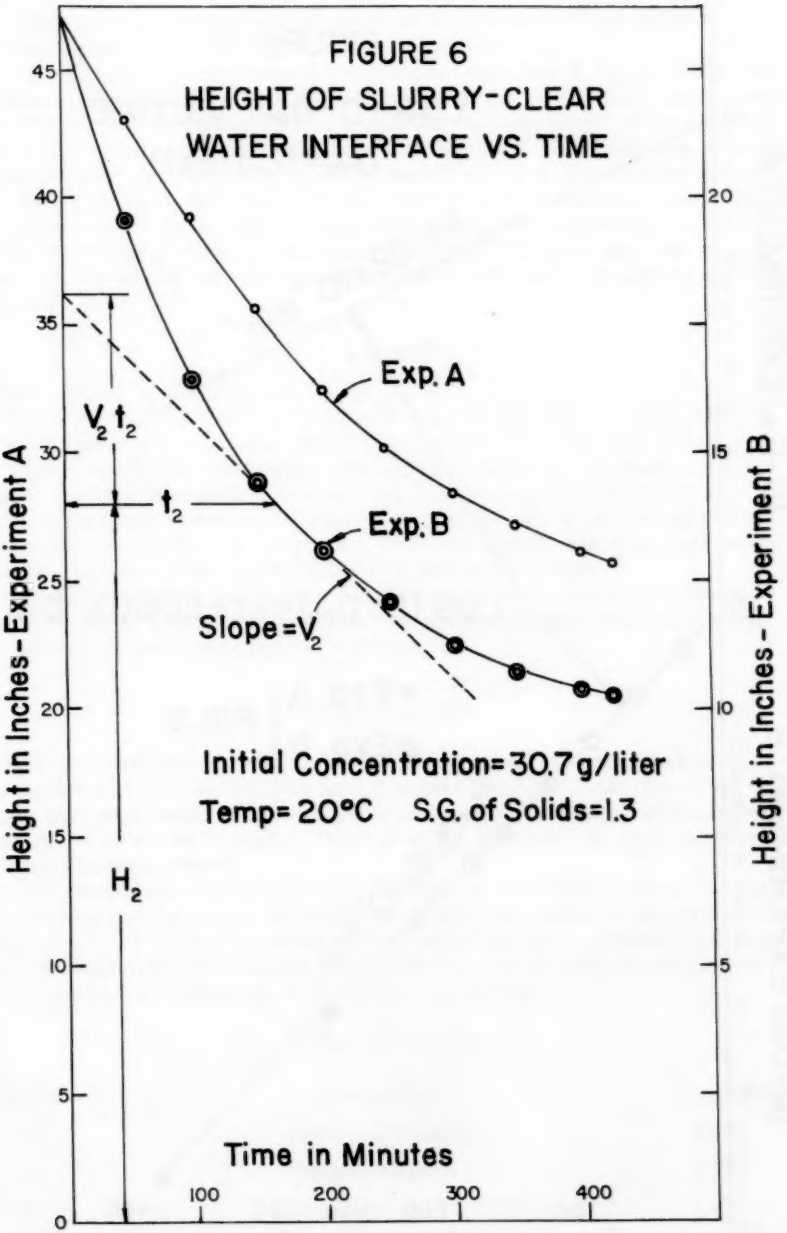


FIGURE 6
HEIGHT OF SLURRY-CLEAR
WATER INTERFACE VS. TIME
Exp. A
Exp. B
$V_2 t_2$
t_2
Slope = V_2
H_2
Initial Concentration = 30.7 g/liter
Temp = 20°C S.G. of Solids = 1.3
Height in Inches - Experiment A
Height in Inches - Experiment B
Time in Minutes
0
5
10
15
20
25
30
35
40
45
100
200
300
400

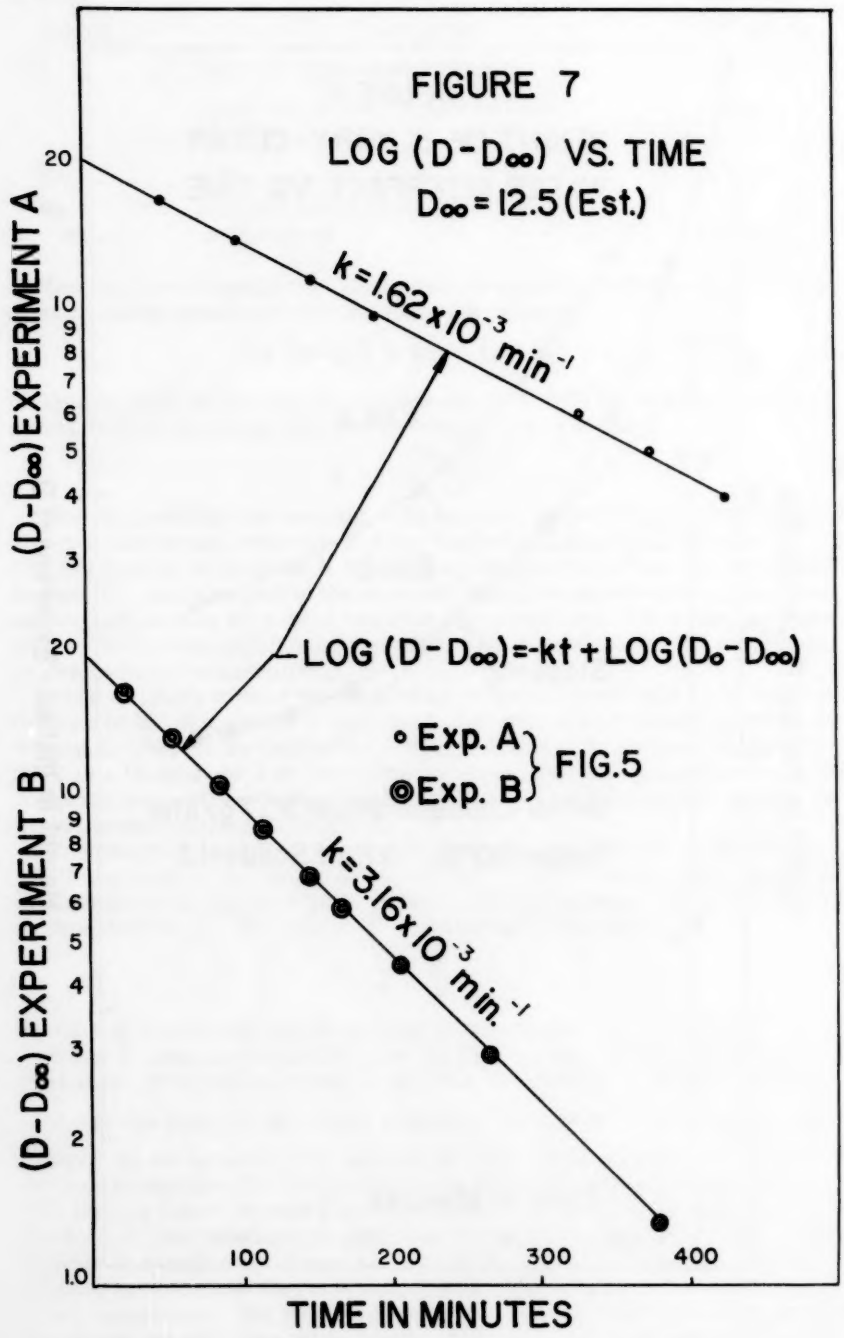


FIGURE 7
LOG (D-D∞) VS. TIME
D∞ = 12.5 (Est.)
k=1.62x10⁻³ min⁻¹
LOG (D-D∞)=-kt + LOG(Do-D∞)
∘ Exp. A
◎ Exp. B
FIG.5
k=3.16x10⁻³ min.⁻¹
(D-D∞) EXPERIMENT A
(D-D∞) EXPERIMENT B
20
10
9
8
7
6
5
4
3
2
1.0
100
200
300
400
TIME IN MINUTES

theoretical near the end of the experiment. An ultimate breakdown of the initial hypothesis is to be expected. In the experiment shown in Figures 6 and 7 theory predicts a ratio of k values of 2.0 for the 10 liter column: 20 liter column. This ratio was obtained experimentally.

Other workers have considered the compression zone in terms of the concentration gradient rather than the rate of fall of the clear water-slurry interface. Comings(6) for example, has shown that the concentration varies with height in a continuous thickener as shown in Figure 5. Furthermore, Comings, Pruiss and DeBord used the area under such a curve in combination with the feed rate of solids to determine the detention time of the solids in a continuous thickener.(12) Now it has already been noted that the slurry concentration in a batch settling test increases logarithmically. Thus the bottoms concentration, C, can be expressed as proportional to the time, t, raised to some power, or,

$$C = Bt^b \tag{10}$$

Where B and b are constants.

Using a slurry of copper hydroxide, George(7) was able to show that in a continuous thickener a similar relationship existed provided the detention time of the solids was used rather than elapsed time. At the same time George showed a correlation between the exponent, b, for both batch and continuous settling based on the relationship of the detention time of the suspension and the solids in a thickener. This correlation was then used as the basis for the use of batch settling tests in thickener design.

Generally speaking, the research done on the compression zone bears more promise of application than that concerned with the hindered settling zone insofar as waste sludges are concerned.

Overall Concepts

While the hindered settling and compression zones are analyzed separately as a matter of convenience, they do not appear that way in nature. Some attempts have been made to develop relationships in the settling of suspensions from one basic set of concepts. Until recently, however, no very satisfactory analysis has been offered.

At the outset, one should note that the passage from the hindered settling zone to compression is not well defined. Therefore, some of the work previously reported for the hindered settling zone may have extended past that zone. Kalinske,(30) for example, suggests that a wide range of settling behavior can be determined from the empirical equation

$$V_c = V - \alpha S_o \tag{11}$$

Symbol	Description	Dimension
v_c	hindered velocity	LT^{-1}
v	Stokes velocity	LT^{-1}
α	Constant	LT^{-1}
s_o	ratio of final volume of settled solids to initial volume of suspension	None

Ward and Kammermeyer,[31] have investigated the relation between the initial and final sludge heights of a column of slurry. But this has the disadvantage of no time relationship.

One important new theory does, however, fit the need for a basic overall concept. Kynch[32] has developed a new approach to the theory of suspension which is based on the postulate that the settling velocity of a particle in a suspension is a function only of the local solids concentration. The settling process can then be determined from a continuity equation without knowledge of the forces involved or the manner in which the solids concentration changes. The theory predicts an upper surface to the dispersion. Furthermore, the velocity of fall at varying concentrations can be determined by the rate of fall of this upper layer with time, given the initial concentration. In other words, a velocity versus concentration curve can be constructed from a batch settling rate provided that the initial concentration is known.

Now a batch of slurry settling in a container will deposit solids on the bottom of the container in such a manner that the concentration will build upwards from the bottom. An important and interesting prediction of the Kynch theory is that a given concentration layer will proceed upwards from the bottom of the vessel at a uniform rate.

Application of these principles has been enhanced by a useful article by Talmage and Fitch.[33] The equations below follow the work of these authors.

Assume a sludge column as in Figure 3 having height H_o and area A. A uniform slurry of concentration C_o occupying this column would contain a weight of solids equal to C_oH_oA. The slurry-clear water interface in such a column was observed to fall at the rate shown in Figure 6, experiment A. Now a given concentration layer, $C_i < C_o$, is propagated upwards at a uniform rate, U_i, from the bottom of the column. When this layer reaches the interface a quantity of solids equal to $C_iAt_i\ (V_i + U_i)$ must have passed the layer where V_i is the settling velocity of particles at concentration C_i and t_i is the elapsed time. Since this constitutes all the solids in the column

$$C_oH_oA = C_iAt_i\ (V_i + U_i) \tag{12}$$

If H_i is the slurry height at time t_i then $U_i = \frac{H_i}{t_i}$

and

$$C_i = \frac{C_oH_o}{(H_i + V_it_i)} \tag{13}$$

As shown on Figure 6, V_i is simply the slope of the settling curve at time t_i. $(H_i+V_it_i)$ is then the intercept of the curve on the vertical axis. Accordingly, it is now a simple matter to measure varying slopes and intercepts. Since C_oH_o is known, C_i for each V_i may be easily computed by means of equation (13). The pairs of values of C_i and V_i may be plotted as in Figure 8 to give a curve depicting concentration versus velocity.

The data of Figure 6, previously described, has been analyzed in this manner. Computed values of C_i and V_i obtained from Figure 6 are shown on Figure 8. The data for both the 10 liter and 20 liter settling columns are seen to fit well together in one curve.

This is, of course, the same set of data used previously in this report for the interpretation of the compression zone. The writer concludes from this that the Kynch theory does extend into the compression zone, although Kynch

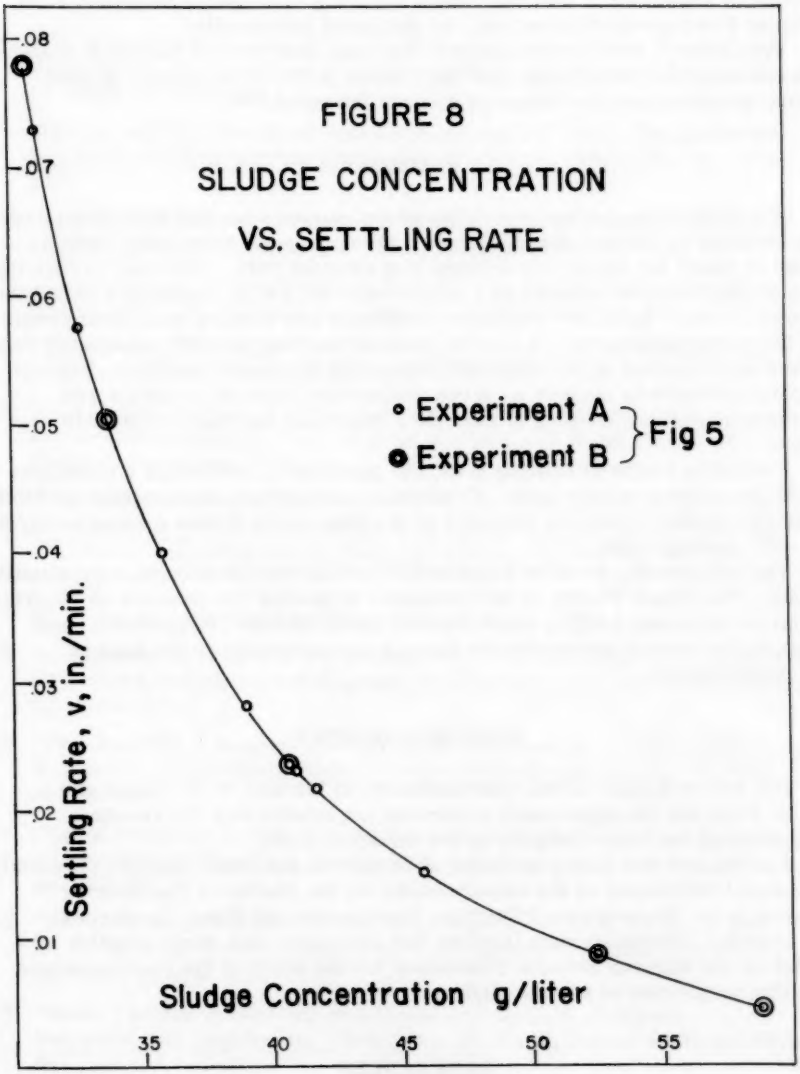


FIGURE 8

SLUDGE CONCENTRATION

VS. SETTLING RATE

did not so indicate. Other data not reported here have been obtained by the writer in repetition of the experiment reported. The shape of the curve in Figure 8 is reproducible but may be displaced horizontally.

This theory, with the extension of Talmage and Fitch to thickener design(33) should have immediate practical application in the waste treatment field. Some acceptance of the theory is already indicated.(34)

SUMMARY

The qualitative mechanism of thickening suspensions has been described as occuring in several zones. Beneath the undermost clear water zone is a zone in which the solids are settling at a constant rate. This rate is less than the Stokes terminal velocity of a single particle, and is sometimes called the hindered rate. Since the hindrance is deemed due to the mutual interference of the particles the ratio of free to hindered settling velocity has usually been taken as a function of the fractional volume of dispersion medium. Experimental evidence to support such conclusions are difficult to obtain with heterogeneous suspensions of flocculent materials as found in waste treatment.

From this hindered settling zone, the particles pass through a transition zone into a compression zone. Evidence is available to substantiate the often expressed opinion that the behavior of the suspension in this zone is analagous to soils consolidation.

The relationship between zones needs further clarification on a quantitative basis. The Kynch Theory is now available to predict the behavior in departure from the hindered settling zone and may carry into the compression zone. This theory seems acceptable for immediate application in the field of thickener design.

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PROCEEDINGS PAPERS

The technical papers published in the past year are identified by number below. Technical-division sponsorship is indicated by an abbreviation at the end of each Paper Number, the symbols referring to: Air Transport (AT), City Planning (CP), Construction (CO), Engineering Mechanics (EM), Highway (HW), Hydraulics (HY), Irrigation and Drainage (IR), Pipeline (PL), Power (PO), Sanitary Engineering (SA), Soil Mechanics and Foundations (SM), Structural (ST), Surveying and Mapping (SU), and Waterways and Harbors (WW), divisions. Papers sponsored by the Board of Direction are identified by the symbols (BD). For titles and order coupons, refer to the appropriate issue of "Civil Engineering." Beginning with Volume 82 (January 1956) papers were published in Journals of the various Technical Divisions. To locate papers in the Journals, the symbols after the paper numbers are followed by a numeral designating the issue of a particular Journal in which the paper appeared. For example, Paper 1113 is identified as 1113 (HY6) which indicates that the paper is contained in the sixth issue of the Journal of the Hydraulics Division during 1956.

VOLUME 82 (1956)

OCTOBER: 1070(EM4), 1071(EM4), 1072(EM4), 1073(EM4), 1074(HW3), 1075(HW3), 1076(HW3), 1077(HY5), 1078(SA5), 1079(SM4), 1080(SM4), 1081(SM4), 1082(HY5), 1083(SA5), 1084(SA5), 1085(SA5), 1086(PO5), 1087(SA5), 1088(SA5), 1089(SA5), 1090(HW3), 1091(EM4)[c], 1092 (HY5)[c], 1093(HW3)[c], 1094(PO5)[c], 1095(SM4)[c].

NOVEMBER: 1096(ST6), 1097(ST6), 1098(ST6), 1099(ST6), 1100(ST6), 1101(ST6), 1102(IR3), 1103 (IR3), 1104(IR3), 1105(IR3), 1106(ST6), 1107(ST6), 1108(ST6), 1109(AT3), 1110(AT3)[c], 1111(IR3)[c]; 1112(ST6)[c].

DECEMBER: 1113(HY6), 1114(HY6), 1115(SA6), 1116(SA6), 1117(SU3), 1118(SU3), 1119(WW5), 1120(WW5), 1121(WW5), 1122(WW5), 1123(WW5), 1124(WW5)[c], 1125(BD1)[c], 1126(SA6), 1127 (SA6), 1128(WW5), 1129(SA6)[c], 1130(PO6)[c], 1131(HY6)[c], 1132(PO6), 1133(PO6), 1134(PO6), 1135(BD1).

VOLUME 83 (1957)

JANUARY: 1136(CP1), 1137(CP1), 1138(EM1), 1139(EM1), 1140(EM1), 1141(EM1), 1142(SM1), 1143(SM1), 1144(SM1), 1145(SM1), 1146(ST1), 1147(ST1), 1148(ST1), 1149(ST1), 1150(ST1), 1151(ST1), 1152(CP1)[c], 1153(HW1), 1154(EM1)[c], 1155(SM1)[c], 1156(ST1)[c], 1157(EM1), 1158 (EM1), 1159(SM1), 1160(SM1), 1161(SM1).

FEBRUARY: 1162(HY1), 1163(HY1), 1164(HY1), 1165(HY1), 1166(HY1), 1167(HY1), 1168(SA1), 1169(SA1), 1170(SA1), 1171(SA1), 1172(SA1), 1173(SA1), 1174(SA1), 1175(SA1), 1176(SA1), 1177(HY1)[c], 1178(SA1), 1179(SA1), 1180(SA1), 1181(SA1), 1182(PO1), 1183(PO1), 1184(PO1), 1185(PO1)[c].

MARCH: 1186(ST2), 1187(ST2), 1188(ST2), 1189(ST2), 1190(ST2), 1191(ST2), 1192(ST2)[c], 1193 (PL1), 1194(PL1), 1195(PL1).

APRIL: 1196(EM2), 1197(HY2), 1198(HY2), 1199(HY2), 1200(HY2), 1201(HY2), 1202(HY2), 1203 (SA2), 1204(SM2), 1205(SM2), 1206(SM2), 1207(SM2), 1208(WW1), 1209(WW1), 1210(WW1), 1211(WW1), 1212(EM2), 1213(EM2), 1214(EM2), 1215(PO2), 1216(PO2), 1217(PO2), 1218 (SA2), 1219(SA2), 1220(SA2), 1221(SA2), 1222(SA2), 1223(SA2), 1224(SA2), 1225(PO)[c], 1226 (WW1)[c], 1227(SA2)[c], 1228(SM2)[c], 1229(EM2)[c], 1230(HY2)[c].

MAY: 1231(ST3), 1232(ST3), 1233(ST3), 1234(ST3), 1235(IR1), 1236(IR1), 1237(WW2), 1238(WW2), 1239(WW2), 1240(WW2), 1241(WW2), 1242(WW2), 1243(WW2), 1244(HW2), 1245(HW2), 1246 (HW2), 1247(HW2), 1248(WW2), 1249(HW2), 1250(HW2), 1251(WW2), 1252(WW2), 1253(IR1), 1254(ST3), 1255(ST3), 1256(HW2), 1257(IR1)[c], 1258(HW2)[c], 1259(ST3)[c].

JUNE: 1260(HY3), 1261(HY3), 1262(HY3), 1263(HY3), 1264(HY3), 1265(HY3), 1266(HY3), 1267 (PO3), 1268(PO3), 1269(SA3), 1270(SA3), 1271(SA3), 1272(SA3), 1273(SA3), 1274(SA3), 1275 (SA3), 1276(SA3), 1277(HY3), 1278(HY3), 1279(PL2), 1280(PL2), 1281(PL2), 1282(SA3), 1283 (HY3)[c],1284(PO3), 1285(PO3), 1286(PO3), 1287(PO3)[c], 1288(SA3)[c].

JULY: 1289(SM3), 1290(EM3), 1291(EM3), 1292(EM3), 1293(EM3), 1294(HW3), 1295(HW3), 1296(HW3), 1297(HW3), 1298(HW3), 1299(SM3), 1300(SM3), 1301(SM3), 1302(ST4), 1303 (ST4), 1304(ST4) 1305(SU1), 1306(SU1), 1307(SU1), 1308(ST4), 1309(SM3), 1310(SU1)[c], 1311(EM3)[c], 1312 (ST4), 1313(ST4), 1314(ST4), 1315(ST4), 1316(ST4), 1317(ST4), 1318 (ST4), 1319(SM3)[c], 1320(ST4), 1321(ST4), 1322(EM3), 1323(AT1), 1324(AT1), 1325(AT1), 1326(AT1), 1327(AT1), 1328(AT1)[c], 1329(ST4)[c].

AUGUST: 1330(HY4), 1331(HY4), 1332(HY4), 1333(SA4), 1334(SA4), 1335(SA4), 1336(SA4), 1337(SA4), 1338(SA4), 1339(CO1) 1340(CO1), 1341(CO1), 1342(CO1), 1343(CO1), 1344(PO4), 1345(HY4), 1346(PO4)[c], 1347(BD1), 1348(HY4)[c], 1349(SA4)[c], 1350(PO4), 1351(PO4).

SEPTEMBER: 1352(IR2), 1353(ST5), 1354(ST5), 1355(ST5), 1356(ST5), 1357(ST5), 1358(ST5), 1359(IR2), 1360(IR2), 1361(ST5), 1362(IR2), 1363(IR2), 1364(IR2), 1365(WW3), 1366(WW3), 1367(WW3), 1368(WW3), 1369(WW3), 1370(WW3), 1371(HW4), 1372(HW4), 1373(HW4), 1374(HW4), 1375(PL3), 1376(PL3), 1377(IR2)[c], 1378(HW4)[c], 1379(IR2), 1380(HW4), 1381(WW3)[c], 1382(ST5)[c], 1383(PL3)[c], 1384(IR2), 1385(HW4), 1386(HW4).

OCTOBER: 1387(CP2), 1388(CP2), 1389(EM4), 1390(EM4), 1391(HY5), 1392(HY5), 1393(HY5), 1394(HY5), 1395(HY5), 1396(PO5), 1397(PO5), 1398(PO5), 1399(EM4), 1400(SA5), 1401(HY5), 1402(HY5), 1403(HY5), 1404(HY5), 1405(HY5), 1406(HY5), 1407(SA5), 1408(SA5), 1409(SA5), 1410(SA5), 1411(SA5), 1412(EM4), 1413(EM4), 1414(PO5), 1415(EM4)[c], 1416(PO5)[c], 1417 (HY5)[c], 1418(EM4), 1419(PO5), 1420(PO5), 1421(PO5), 1422(SA5)[c]. 1423(SA5), 1424(EM4), 1425(CP2).

c. Discussion of several papers, grouped by Divisions.

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